STUDY OF UNIFIED POWER QUALITY CONDITIONER FOR POWER QUALITY IMPROVEMENT

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STUDY OF UNIFIED POWER QUALITY CONDITIONER FOR POWER QUALITY IMPROVEMENT

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By

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May 2015

Dedicated to

My

Beloved Parents

NATIONAL INSTITUTE OF TECHNOLOGY

ROURKELA

CERTIFICATE

This is to certify that the thesis entitled, **"Study of Unified Power Quality Conditioner for Power Quality Improvement"** submitted by **Rajiv Kumar Sinku (Roll No. 213EE5352)** in partial fulfilment of the requirements for the award of Master of Technology Degree in Electrical Engineering with specialization in Industrial Electronics during 2014 -2015 at the National Institute of Technology, Rourkela is an authentic work carried out by him under my supervision and guidance.

To the best of my knowledge, the matter embodied in the thesis has not been submitted to any other University / Institute for the award of any Degree or Diploma.

Place: NIT Rourkela

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DECLARATION

I hereby declare that the investigation carried out in the thesis has been carried out by me. The work is original and has not been submitted earlier as a whole or in part for a degree/diploma at this or any other institute/University.

Rajiv Kumar Sinku

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ABSTRACT

In a powers system network there are many problems related to power quality. So to improve power quality of a system we use different devices such as active power filters. Active power filters are classified into two types that is Shunt Active Power Filter (APF) and Series Active Power Filter (APF) and combination of both is known as UPQC (Unified Power Quality Conditioner). Here we have done simulation of Shunt Active Power Filter, Series Active Power Filter and Unified Power Quality Conditioner. Shunt APF is used to mitigate the problems due to current harmonics which is because of non-linear load and make source current sinusoidal and distortion free. The control scheme used is hysteresis current controller using “p-q theory”. Series APF is used to mitigate problems caused due to voltage distortion and unbalance present in source voltage and make load voltage perfectly balanced and regulated. The control scheme used is Hysteresis voltage controller by using a-b-c to d-q transformations. Then Shunt APF and Series APF is combined for designing UPQC and by this current harmonics in load current and voltage unbalances in source voltage both are removed and source current becomes sinusoidal and load voltage becomes perfectly balanced.

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List of Abbreviation

APF	Active Power Filter
FFT	Fast Fourier Transform
DSTATCOM	Distribution Static Compensator
DVR	Dynamic Voltage Regulator
HB	Hysteresis Band
LPF	Low Pass Filter
HPF	High Pass Filter
PCC	Point of Common Coupling
PLC	Programmable Logic Controller
PLL	Phase Locked Loop
THD	Total Harmonic Distortion
UPQC	Unified Power Quality Conditioner
VSI	Voltage Source Inverter
CSI	Current Source Inverter
UVT	Unit Vector Template

Chapter 1

INTRODUCTION

1.1 Overview

In today's world there is great importance of electrical energy as it is the most famous from of energy and all are massively relying on it. Without supply of electricity life cannot be imagined. At the same time the quality and continuousness of the electric power supplied is also very important for the efficient functioning of the end user equipment. Many of the commercial and industrial loads require high quality undisturbed and constant power. Thus maintaining the qualitative power is topmost important in today's world.

Due to power electronics devices there is serious effect on quality and continuousness of electric supply. Because of power electronics devices there is uninterrupted power supply, flicker, harmonics, voltage fluctuations e.tc. There is also PQ problems such as voltage rise/dip due to network faults, lightning, switching of capacitor banks. With the excessive uses of non-linear load (computer, lasers, printers, rectifiers) there is reactive power disturbances and harmonics in power distribution system. It is very essential to overcome this type of problems as its effect may increase in future and cause adverse effect.

Traditionally passive filters were used for reactive power disturbances and harmonics generation but there is many problems with them like they are large in size, resonance problem, effect of source impedance on performance.

Active Power Filters are used for power quality enhancement. Active power filters can be classified according to system configuration. Active power filters are of two types series and shunt. Combining both series APF & shunt APF we get a device known as UPQC. UPQC eliminates the voltage and current based distortions together.

A Shunt APF eliminates all kind of current problems like current harmonic compensation, reactive power compensation, power factor enhancement. A Series APF compensates voltage dip/rise so that voltage at load side is perfectly regulated. The Shunt APF is connected in parallel with transmission line and series APF is connected in series with transmission line. UPQC is formed by combining both series APF and shunt APF connected back to back on DC side.

In this controlling techniques used is hysteresis band controller using "p-q theory" for shunt APF and hysteresis band controller using Park's transformation or dq0 transformation for series APF. UPQC is made by combining both shunt APF and series APF. UPQC is used to eliminate all problems due to current harmonics and voltage unbalances & distortions and improve power quality of a system. UPQC is a very versatile device as at same time it mitigates the problem both due to current and voltage harmonics. In this thesis power quality of system was improved by using UPQC. First simulation of shunt APF was done after that series APF was done. And after that combining both device simulation of UPQC was done.

1.2 Literature Review

Now a day’s power quality has become the most essential factor for both power suppliers and consumers due to the degradation of the electric power energy market. Efforts are being made to improve power quality. Today in this modern world power quality has become a great issue. As many industries and for domestics use we need a voltage and current free from all types of harmonics and unbalances. Due to problems in power quality there is development of many methods to improve power quality by using active power filters [1] [2]. The concept of power was introduced by the N.G. Hingrani [3]. Power electronics devices consists of a diode, thyristors, IGBT, diodes [4]. The active power filters are used to remove harmonics from current of load side and make supply current completely sinusoidal, and it also mitigate the problems of supply voltage imbalance i.e voltage rise/dip and make voltages at load side balanced of equal magnitude. The active power filters can be combined together and made to remove both problems due to voltage and current harmonics. There are wide range of controlling techniques for active power filters [5].

The [6] reactive power theory was used to do simulation of three phase three wire line which is valid for both of the transient and steady state. The physical meaning of instantaneous reactive power theory was described in [7]. The instantaneous reactive power theory with the non-linear loads is described in [8]. The DVR model is discussed in [9] for removal of all kinds of voltage related problems. Here the operating system consist of PLL and Park’s transformation is used for simulation. In [10] three phase simulation of series active power filter is done for removal of voltage unbalances in supply side and make load voltage balanced and regulated. In chapter [11] the operation of DSTATCOM is explained. In [12] the operation of three phase four wire shunt APF is explained which is used to suppress load current harmonics which is due to non-linear loads. As the power quality is the most important factor so to get improved power quality and removal of all type of harmonics from voltage and current we study UPQC which is a very versatile device and can be used for both mitigate the problems due to current harmonics and voltage disturbances [13]. The voltage source inverter active filters are used for removal of power quality problems [14] [15]. The shunt active power filer is used to remove all the problems related to current harmonics and reactive power compensation so that the power quality will improve and source current will become completely sinusoidal, it is also used for power factor correction [16]. A series APF removes all kind of problems which arises due to voltage like voltage distortion, fluctuations, voltage dip/rise and make load side voltage balanced and equal in magnitude. [17]. A UPQC is a device which is formed by connecting a series APF and shunt APF back to back through DC capacitor [18]. This vast range of objectives is achieved either individually or in combination, depending upon the requirements and controlling techniques and configuration which have to be selected appropriately [19]. In [20] UPQC control techniques are introduced for removal of harmonics. A unit vector template generation is explained in this paper. In [21] UPQC control strategy was discussed for three phase four wire system, here series APF and shunt APF are connected back to back with the help of DC capacitor and unit vector template control strategy was used for series APF. In [22] a new control strategy for UPQC was discussed for removal of harmonics under non-ideal mains voltage and unbalanced loads. The power quality is improved near PCC (point of common coupling). In [23] a unified quality conditioner was developed for both removal of harmonics and reactive p16wer compensation. UPQC was studied with both R-L load and R-C load. Here the PI controller were used to get the amount of power loss in the UPQC. As we know that in today’s world due to non-linear loads which is because of power electronics devices and due to faults in the power systems there arises many power quality problems so to remove this problems we use different types of filters. Earlier passive filters were used but because of their larger size and resonance problems the use of passive filters are not recommended. So now a days active power filters are used, which are classified according to different methodology. But our main consideration in Shunt APF, Series APF, and UPQC. A UPQC is most efficient device as it removes all kind of problems related to power quality. But Shunt APF only operates for current related problems whereas series APF operates for voltage related problems. So UPQC is the device mainly used for power quality problem. There are many control techniques used for shunt APF, series APF and UPQC. For shunt APF we can use “p-q theory” and hysteresis current controller. Also we can use Park’s transformation that is dq0 theory. There is also SPWM techniques used for shunt APF simulation. For series APF control techniques used is Park’s transformation and hysteresis voltage controller. Also we can use SPWM techniques and SVPWM (space vector pulse width modulation) technique for series APF.

For UPQC control technique used in this thesis is hysteresis controller.

1.3 Research motivation

Due to increase in use of power electronics devices in the power system and due faults in the system the electric power supply gets interrupted and power quality is highly effected. There is contents of harmonics in currents and voltages. There are faults like flicker, increase in voltage fluctuations. The telecommunication, industries, and semiconductor manufacturing industries are more sensitive to power quality problems as they need high quality of power. So here we have studied how to remove power quality problems with the help of active power filters. Shunt APF is used to compensate the problems caused by load current harmonics and make the source current completely sinusoidal. Series APF is used to mitigate problems related to voltage dip/rise in source voltage and make load voltage completely regulated. UPQC is used to solve all problems related to voltage and current harmonics and improve power quality.

1.4 Thesis Objective

The objective of this project are

- To explore the techniques for removal of current harmonics and mitigate the voltage swell, sag.
- Study the UPQC model for power quality improvement.
- Investigate Shunt APF for compensating load current harmonics and so that current drawn from supply is completely sinusoidal.
- Investigate Series APF so to mitigate voltage dip and rise from source voltage and make load voltage perfectly balanced.

1.5 Organization of Thesis

In Chapter 1 there is brief description about the thesis and paper studied for organization of thesis and the summary of work done by different researchers and how I was motivated to do this project, and objective of thesis.

In Chapter 2 there is a discussion about power quality, and what are the problems effecting power quality of a system, different types of loads, harmonics indices.

In Chapter 3 there is discussion about UPQC, different control strategy of UPQC, parts of UPQC i.e. Shunt APF and series APF. And different control strategy required for simulation of both.

In Chapter 4 simulation results are given and they are discussed.

In Chapter 5 conclusions are discussed along with future scope and references.

Chapter 2

POWER QUALITY

2.1 Introduction

In our day to day life, and in many industries there is very huge use of power electronics devices, Programmable logic circuits (PLC), semiconductor devices, and adjustable speed drives due to this there is power quality problems. There is also many external and internal factors that effect the quantity and quality of power delivered. Many network faults, switching of capacitor banks, voltage sag/swell, lightning, and harmonics also cause power quality problems. Mainly loads work at 50 Hz and 60 Hz frequencies. But there are many loads which work at integer multiple of 50 Hz and 60 Hz frequencies. Because of these loads there is harmonics in power system.

2.2 Linear and Non- linear loads

2.2.1 Linear load

The loads which have current and voltage waveform sinusoidal are linear loads. The current at any time is proportional to voltage. Linear load only change relative timing (phases) between current and voltage there is no change in shape of current waveform. According to Ohm's law

$$\mathrm{I(t)} = \frac{\mathrm{V(t)}}{\mathrm{R}} \tag{2.1}$$

According to this law if waveform of voltage is sinusoidal then the waveform of current will also be sinusoidal.

Linear loads are capacitor and inductor. If capacitor is in load side then the current will lead voltage. If inductor is in load side then voltage will lead. So waveforms in both case will be out of phase. Power factor defined in case of linear load

$$\text{Power Factor} = \frac{\text{Real power}}{\text{Apparent power}} = \cos\emptyset \tag{2.2}$$

Examples of linear loads are given in Table 2.1

Table 2.1 Examples of linear load

Resistive components	Inductive components	Capacitive components
• Lightning Heaters • Incandescent Lamps	• Induction motors • Induction generators (windmills)	• Insulated cables • Underground cables • Capacitors used in harmonic filters

2.2.2 Non-Linear loads

In non-linear loads the shape of current waveform changes its shape from original shape. Non-linear loads produces harmonics with original fundamental component of AC current. Non-linear loads examples are power electronics devices like BJT, MOSFET. Given in Table 2.2

Table 2.2 Examples of non- linear load

Power Electronics	ARC devices
• Power converters • Inverters • Cranes • Computers • UPS • Refrigerators • Battery chargers • Elevators Steel mills • Power supplies	• ARC furnaces • Welding machines

2.3 Major power quality problems

2.3.1 Short duration voltage variation

Due to faults there is voltage rise (swells), voltage dip (sag), or complete loss of voltages (interruptions) which are temporary for certain interval of time depending upon the type of fault occurred and location of fault. The duration is around 1 min for short voltage variation. Also if duration of fault is for few millisecond then it is short duration voltage variation.

(i) Voltage sag:- Voltage sag is also called voltage dip . The rms line voltage decreases to 10 % to 90 % of nominal line voltage. The time interval for voltage dip is about 0.5 cycle to 1 min. The equipment which cause voltage dip are induction motor starting etc. Voltage dip is shown in fig.2.1

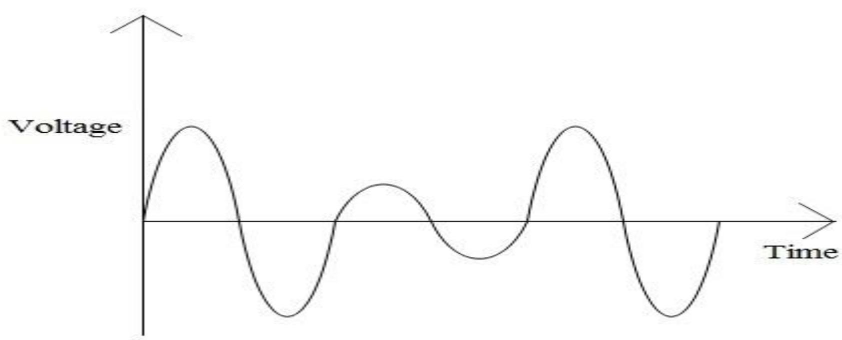


Fig.2.1 Voltage sag

(ii) Voltage swell:- Voltage swell is also called voltage rise. The rms line voltage increases from 1.1 % to 1.8% of nominal line voltage. The duration for voltage rise is around 0.5 cycle to 1 min. The voltage swell is caused due to energizing the large capacitor bank and shutting down the large loads. Voltage swell is shown in fig.2.2

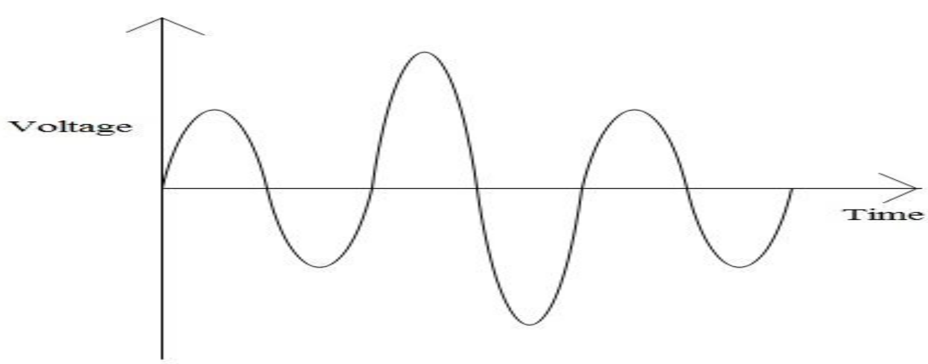


Fig.2.2 Voltage swell

(iii) Interruption:- Interruption is degradation in current or line voltage up to 0.1 pu of the nominal value. It is for the time period of 60 seconds and not going beyond it. The cause of interruption are failures in equipment, faults in power systems, control malfunctions. It is shown in fig.2.3

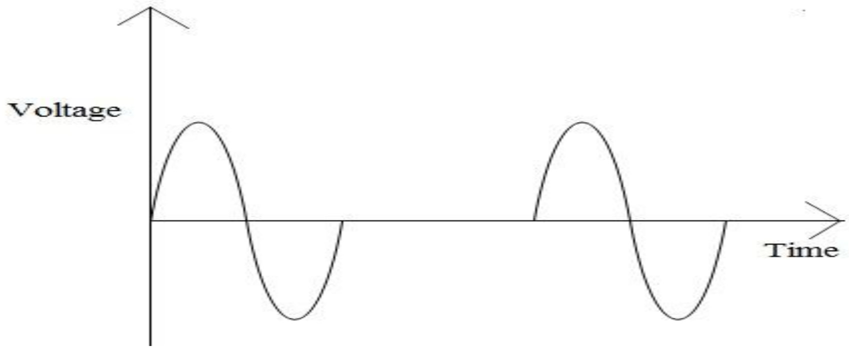


Fig.2.3 Voltage interruption

2.3.2. Long- Duration voltage variation

The long duration voltage variations are caused because of sustained interruptions, under voltages and over voltages.

(i) Sustained interruptions:- When there is zero supply voltage for a interval of time more than 60 sec, it is considered as sustained interruption in case of long duration voltage variation.

(ii) Under voltages:- It is the reduction in rms ac voltage to lower than 90 % at power frequency for a time interval 60 sec or may be greater than it. The switching off of capacitor banks and switching on of loads cause under voltage as far as voltage regulation device on the system bring back the voltage to the given tolerance limits. The under voltage is also caused due circuits which are overloaded.

(iii) Over voltages:- It is the rise in rms ac voltage to more than 110 % at power frequency for a time interval of more than 60 sec. Over voltages are caused due to the wrong tap settings of transformers and switching of loads.

2.3.3 Voltage fluctuations

Fluctuations in voltage is irregular or repeated variations in magnitude of source voltage due to sudden change in real and reactive power drawn by the load. The characteristics of voltage fluctuation depend upon type of loads. The magnitude of voltage fluctuation does not rise above

10% of nominal supply voltages. The Lamp flicker is the effect of voltage fluctuations. Loads that cause fluctuations in voltages are arc furnaces, arc welders, air conditioner units, rolling mills, cycloconverters, and equipment with excessive motor speed changes. Voltage fluctuations are shown in fig.2.4

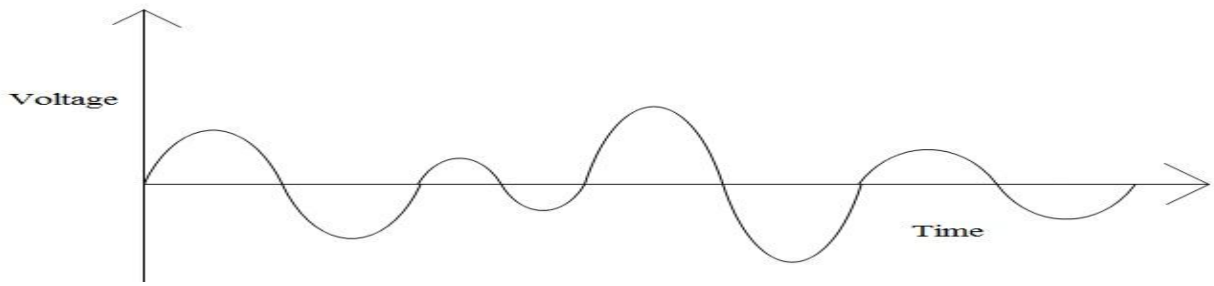


Fig.2.4 Voltage fluctuation and flicker

2.3.4 Voltage Unbalance

Voltage unbalances occur when there is difference in magnitude of phases or line voltages and phase angle is different from balanced conditions. Voltage unbalance is due to different loads in the phases causing drops in voltages at phase – line impedance.

2.3.5 Transients

Transients are sudden & small change in current and voltage signals for a very less period of time.

(i) Impulsive transients:- Impulsive transient are variation in current, voltage or both on power line in one direction (unidirectional). The causes of impulsive transients are switching in power distribution systems, inductive loads switching, lightning. The impulsive transients can be removed with help of zener diode which suppresses the transient voltage. Impulsive transients are shown in Fig.2.5

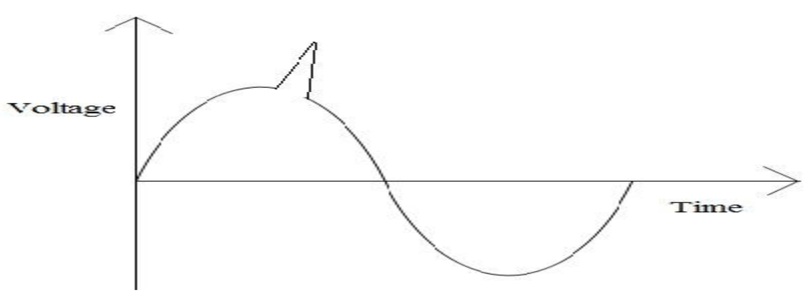


Fig.2.5 Impulsive Transient

(ii) Oscillatory transients:- Oscillatory transients are transients which have swing (bidirectional) i.e. rapid change of polarity of current , voltage or both on power line. Causes of this is Capacitors switching which help in power factor correction. It is given in fig.2.6

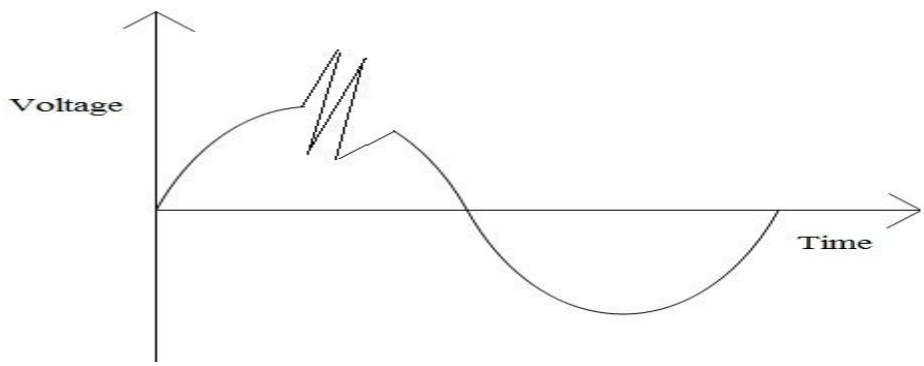


Fig.2.6 Oscillatory Transient

2.3.6 Waveform Distortion

A power system network tries to generate a sinusoidal voltage and current waveform but due to certain problem it is not able to generate the sinusoidal nature waveform and distortions occurs.

There are many causes of waveform distortion:-

(i) DC Offset:- A DC offset is a presence of DC voltage or current in a AC power system. Due to DC offset the signal shifts from its actual reference position.

(ii) Noise:- Noise is unwanted electrical signals. It is caused due to interference in communication network. The unwanted signals are superimposed in powers system current or voltage which are in phase or in neutral conductors.

(iii) Notching:- Notching is voltage disturbances caused periodically due to transfer of current from one phase to another when power electronics equipment are commutated.

(iv) Harmonics:- The harmonics are sinusoidal currents and voltages which operate at frequencies that are integer multiple of fundamental frequency. The 50 Hz and 60 Hz are fundamental frequency. The harmonics are caused due to non- linear loads. Total harmonic distortion (THD) of voltage is measured by

$$V_{THD} = \frac{\sqrt{\in_{n=2}^{\infty} V_n^2}}{V_1} \tag{2.3}$$

Where V_1 is rms magnitude of fundamental component & V_n is rms magnitude of component when n= 2…….. ∞.

(v) Inter harmonics:- Inter harmonics are harmonics which are not at the frequencies that are integer multiple of fundamental frequency (50 Hz or 60 Hz). That are caused due to induction furnaces, cycloconverters, arc furnaces, static frequency converters.

2.3.7 Frequency variations

In a power system many equipment and devices are made to operate at fundamental frequency. But there is variations in frequency due sudden disturbances in supply or demand. Frequency variations are mainly caused due to failure of generators and switching of loads.

2.4 Power definitions

Definitions of apparent power, active power, reactive power, complex power, power factor are given below:-

(i) Apparent power:- It is multiplication between rms voltage & rms current in circuit. It is given by

$$S = V_{rms} \times I_{rms} \tag{2.4}$$

Where $$V_{rms} = \sqrt{\frac{1}{T}\int_0^T v^2(t)dt} = \sqrt{\in_{k=1}^{\infty} V_k^2} \tag{2.5}$$

$$I_{rms} = \sqrt{\frac{1}{T}\int_0^T i^2(t)dt} = \sqrt{\in_{k=1}^{\infty} I_k^2} \tag{2.6}$$

Here V_k and I_k are rms value of k^{th} order harmonic component of Fourier series and T is time period of fundamental component.

(ii) Active power:- It is the real power drawn by the circuit while doing any useful work. It is measured in watts.

$$P = \in_{k=1}^{\infty} P_k = \in_{k=1}^{\infty} V_k I_k \cos \emptyset_k \tag{2.7}$$

here $\emptyset_k$ is displacement angle of each pair k^{th} order harmonic component of current & voltage.

(iii) Reactive power:-It is energy stored and discharged by capacitors, induction motor, transformers etc. . It is measured in volt-ampere reactive (VAR).

$$Q = \in_{k=1}^{\infty} Q_k = \in_{k=1}^{\infty} V_k I_k \sin \emptyset_k \tag{2.8}$$

2.5 Harmonics

Harmonics are sinusoidal voltage & current which operate at integer multiple of fundamental frequency.

2.6 Harmonics indices

In power Quality Corporation some index values has been developed to determine the service quality and distortions caused due to harmonics. The two indexes mostly used are total harmonic distortions (THD) and total demand distortion (TDD). Harmonics indices are given below:-

2.6.1 Total harmonic distortion (THD):

The THD of a signal is measurement of harmonic distortion present in it. Low THD means there is reductions in heating, losses, and peak currents in a power systems. THD is measured in percentage. THD is given as

$$\text{THD} = \frac{\text{rms value of all harmonic component of a signal}}{\text{rms value of fundamental component}} \tag{2.9}$$

$$\text{THD} = \frac{\sqrt{}(\text{Y}_2 + \text{Y}_3 + \cdots \ldots\ldots\ldots\ldots\ldots + \text{Y}_\text{H})}{\text{Y}_1} \tag{2.10}$$

Here H is the order of harmonic component and Y_1 is the fundamental component of signal.

2.6.2 Total Demand Distortion (TDD):

It is described as root sum square value of harmonic current to maximum demand load current. When TDD is calculated rather than THD in a system than there is comparing between actual load of the system to the maximum load which avoid the end customer from unreasonably penalized when load is lighter than maximum load.

$$\text{TDD} = \sqrt{\frac{\text{sum of squares of amplitude of all harmonics}}{\text{square of maximim demad load current}}} \times 100\% \tag{2.11}$$

$$TDD = \frac{\sqrt{\in_{H=2}^{H_{max.}} I_H^2}}{I_L} \tag{2.12}$$

Here I_L is maximum demand load current at the point of common coupling (PCC) and H is the order of harmonic component of current.

2.7 Problems caused by harmonics

Due to harmonics there is problems in supply system and also in the installation and user ends and also. There are many problems caused due to harmonics

2.7.1 Harmonics problems in an installation

Problems due to Current harmonics:

(i) Transformers overheating:- Due to harmonic current there is heating in transformers this is mainly because of two reasons:-

- Due to harmonic current the rms current of transformer increases more than its capacity causing losses.

- Harmonic current component increases eddy current losses as it is directly proportional to square of frequency.

(ii) Skin effect:-The phenomenon of alternating current to flow at exterior surface of conductor is known as skin effect. Due to harmonics current the skin effect is more as skin effect increases with increase in frequency. Skin effect is normal at fundamental frequency but it increases as frequency increases and due to harmonics frequency increases.

(iii) Neutrals overloading:-The voltage waveform in three phase system has 120^0 angle displaced between phase and neutral. When loads are unbalanced a net balance current flows in neutral. Due to harmonics there is addition of current in neutral but balanced current cancel outs.

(iv) Circuit Breaker Tripping:-Circuit breakers operate by adding the current of phases & neutral conductors, if the current is not within the limit it disconnects the load from circuit. Due to harmonics tripping can occur.

Problems due to voltage harmonics:-

(i) Distortion in voltages:-There is distorted voltage drop in transmission line because of transmission line impedance which is caused because of distorted load current which is due to non-linear loads.

(ii) Induction Motors:- Due to harmonic voltage distortion there is eddy current losses in motors same as transformers. Also due to harmonics there is stator losses etc.

Chapter 3

UNIFIED POWER QUALITY CONDITIONER

3.1 Introduction

Basically UPQC (Unified Power Quality conditioner) is a equipment which is used for compensate for voltage distortion and voltage unbalance in a power system so that the voltage at load side is completely balance and sinusoidal & perfectly regulated and also it is used to compensate for load current harmonics so that the current at the source side is perfectly sinusoidal and free from distortions and harmonics. UPQC is a combination of a Shunt Active power filter and Series Active power filter. Here Shunt Active power filter (APF) is used to compensate for load current harmonics and make the source current completely sinusoidal and free from harmonics and distortions. Shunt APF is connected parallel to transmission line. Here Series APF is used to mitigate for voltage distortions and unbalance which is present in supply side and make the voltage at load side perfectly balanced, regulated and sinusoidal. Series APF is connected in series with transmission line. UPQC consists of two voltage source inverters connected back to back through a DC link capacitor in a single phase, three phase-three wire, three phase-four wire configuration. The inverter in shunt APF is controlled as a variable current source inverter and in series APF is controlled as a variable voltage source inverter. Earlier passive filters where also used for compensation of harmonics and voltage distortion but due to their many disadvantages they are not used nowadays.

3.2 Active Power Filter

Traditionally passive filters were used for power quality improvement, the passive filters consists of combination of capacitor, inductor and resistor. Passive filters are used for harmonic filtering. Passive filters doesn’t depend upon the external power source. It has many drawbacks such as it is larger in size, resonance problem, effect of source impedance on performance, fixed compensation characteristics. So active power filters (APF) came as alternate solution for passive filters. Active power filters removes harmonics and not have drawbacks such as passive filters. Active power filters are classified as are shown in fig.3.1

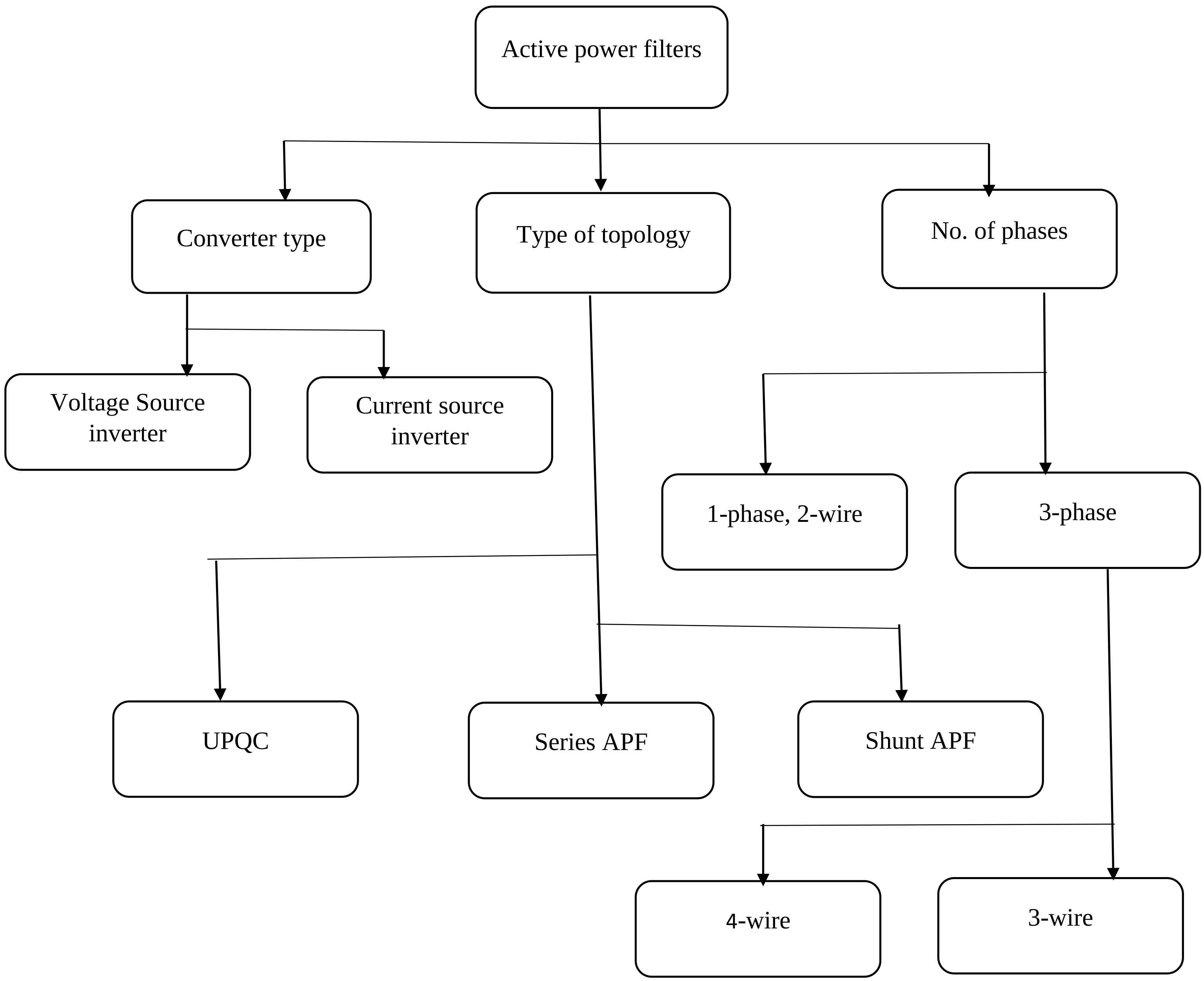


Fig. 3.1 Active power filter classifications

3.3 Basic configuration of UPQC

Fig.3.2 shows basic configuration of UPQC. UPQC mainly consists of:-

- **Series APF:-** In a transmission line series APF is generally connected in series. It is connected to the transmission line with the transformer. Series APF is a voltage source inverter connected in series with transmission line. It is used to compensate or mitigate the problems which comes due to voltage distortions and voltage unbalances. The series APF injects a compensating voltage so that load voltage will be perfectly balanced and regulated. Controlling of series inverter is done by PWM (pulse width modulation) techniques. Here we used Hysteresis band PWM techniques as it implementation is easy. Also its response is fast. Its details are explained in subsequent sections.

- **Shunt APF: -** In a transmission line shunt APF is generally connected in parallel. Shunt APF is used to compensate for distortions & harmonics which are produced due to current. Due to non- linear load there is harmonics in load current, so to keep source current completely sinusoidal and distortion free we uses Shunt APF. Shunt APF injects compensating current so that the source current is completely sinusoidal and free from distortions. Controlling of Shunt APF is done by hysteresis band PWM techniques. In hysteresis band PWM techniques output current follows the reference and current and is within the fixed hysteresis band.

- **Series Transformer:-** The necessary voltage which is generated by series APF so that the voltage at load side is perfectly balanced and regulated i.e. Sinusoidal is injected into the transmission line with the help of these transformers. The series transformer turns ratio should be suitable so that injected voltage is suitable such that it injects a compensating voltage which will completely make the load side voltage balanced and also it reduces the current flowing through series inverter.

- **Low Pass Filter:-** Low pass filter is used at the output of series inverter so that the high frequency voltage components are removed which is produced due to switching of Voltage source inverter

- **High pass filter:-** High pass filter is used at output of shunt inverter so that the ripples which are produced due to currents switching are absorbed.

❖ **DC link capacitor:-** The two voltage source inverter are connected back to back through a DC capacitor. DC capacitor is provides a DC voltage for working of both the inverter. The DC capacitor also provides a real power difference between source and load during the transient period and also acts as a energy storage elements. During steady state real power supplied by source should be equal to the sum real power demand of load & a small amount of power which compensates for active filter. DC capacitor voltage should be equal to reference value but due to disturbance in real power balance between source and load due to change in load conditions the DC capacitor value is changed from reference value.

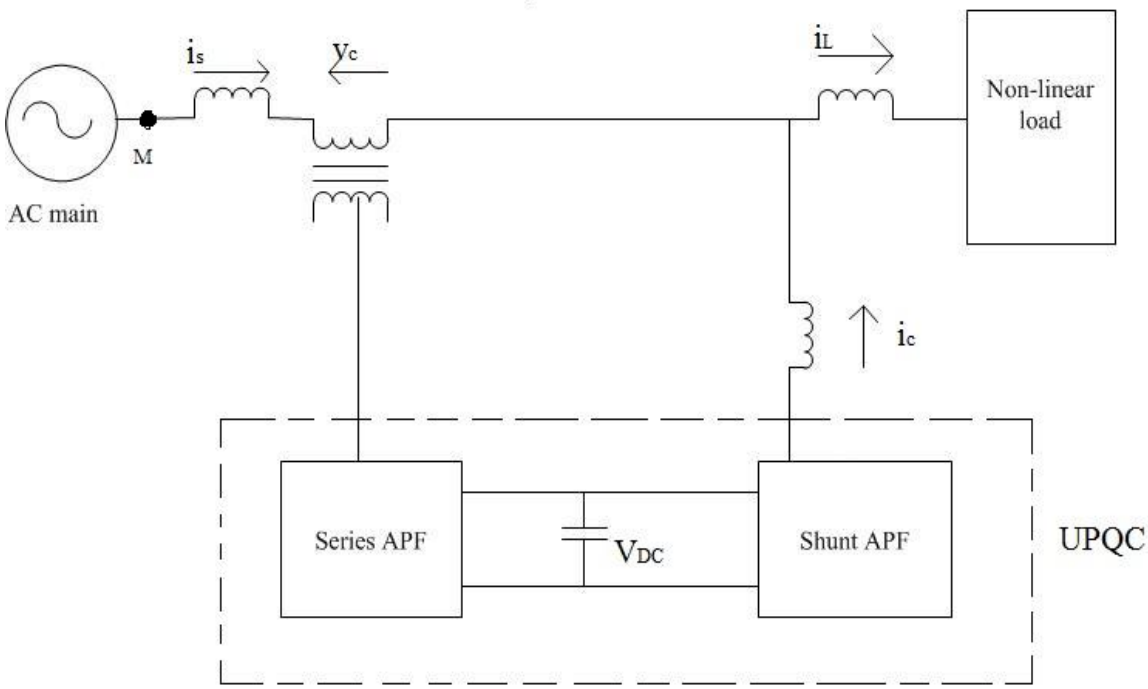


Fig 3.2 Configuration of UPQC

3.3.1 Operation of UPQC:-

As given in fig.3.2 v_s is source voltage, v_c is series compensation voltage, i_s =source current & i_L is load current. The source voltage contains a positive, negative & zero & also the harmonic components. The voltage at M is written as

$$v_s = v_{1n}(t) + v_{1p}(t) + \in_{k=2}^{\infty} v_k(t) \tag{3.1}$$

Eq^n (3.1) can also written as

$$v_s = v_{1n}(\sin(wt + \theta_{1n})) + v_{1p}(\sin(wt + \theta_{1p})) + \in_{k=2}^{\infty} v_k(kwt + \theta_k) \tag{3.2}$$

Here v_{1n}, v_{1p}. are fundamental frequency of component of negative sequence and positive sequence. And v_k is the harmonic component & $\theta_{1n}, \theta_{1p}, \theta_k$ are phase angle of voltages.

3.3.2 UPQC configuration:-

Generally UPQC can be configured in two ways by connecting unit to terminal voltage v_t at PCC (point of common coupling).

- Left Shunt UPQC (fig 3.2):- In this the shunt compensator (i_c) is placed in left side of series compensator (v_c).
- Right Shunt UPQC (fig 3.3):- In this shunt compensator (i_c) is placed in right side of series compensator (v_c).

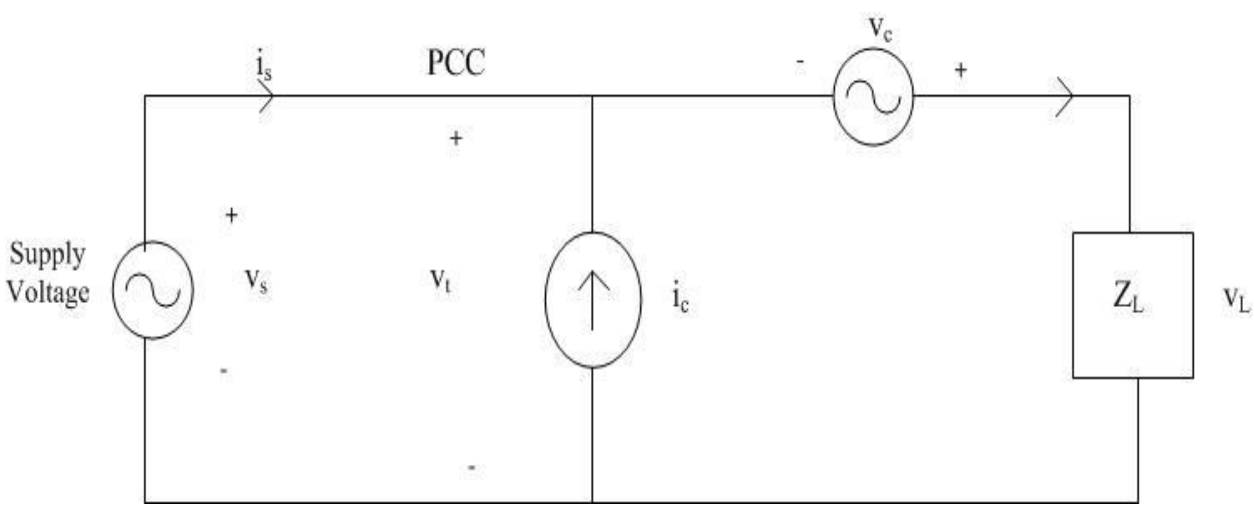


Fig. 3.3 Left shunt UPQC

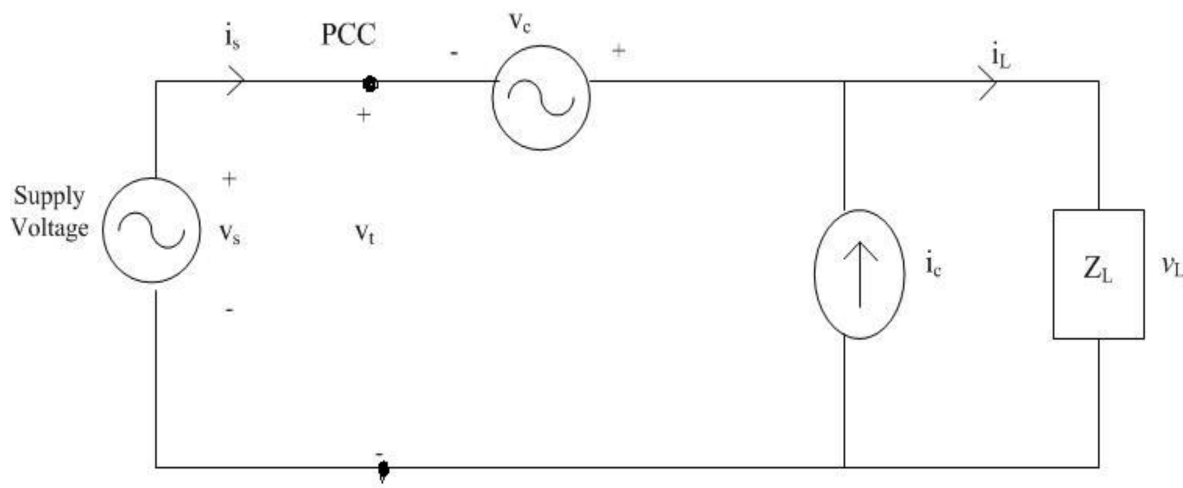


Fig 3.4 Right Shunt UPQC

As shown in the fig. 3.4 Right shunt UPQC has better performance than left shunt UPQC so generally Right shunt UPQC is used.

3.3.3 Power flow analysis of UPQC in steady state

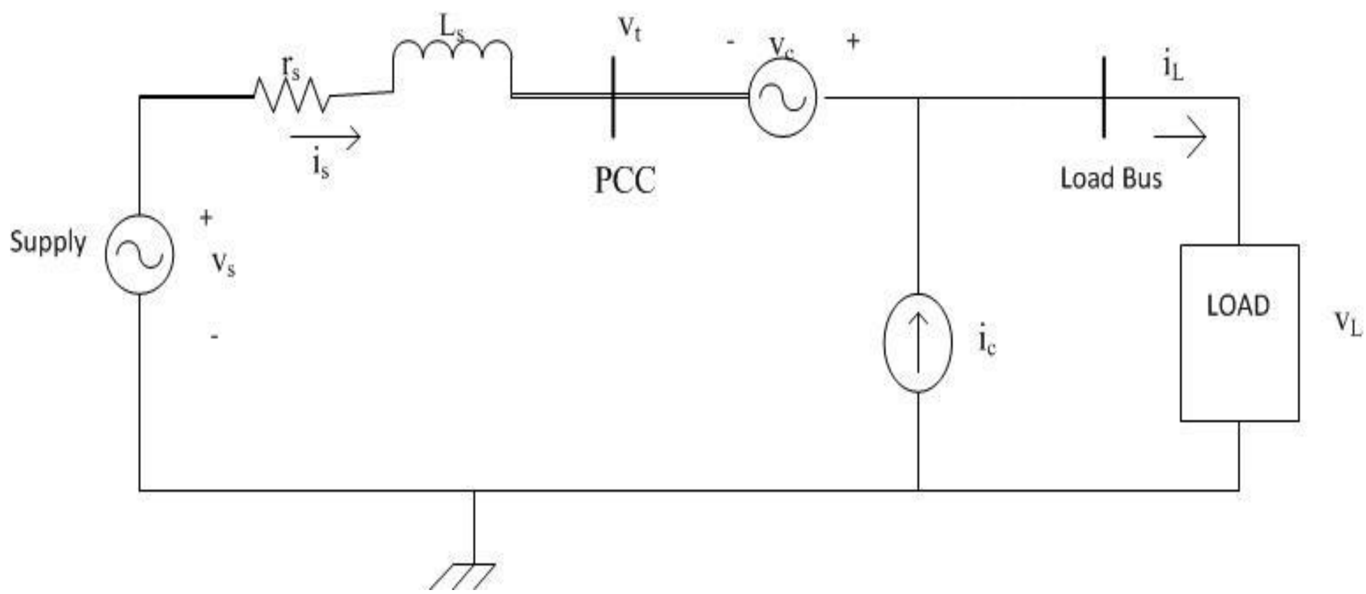


Fig. 3.5 Circuit diagram of UPQC

Here v_s = source voltage

i_s = source current

v_t = terminal voltage at PCC

v_L = load voltage

i_L = load current

i_c = compensating current of shunt APF

v_c = injected voltage by series APF

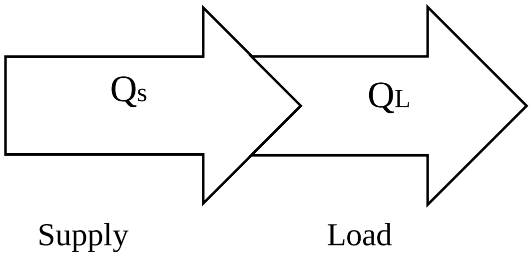
r_s & L_s = resistance and inductance of source

k = source voltage fluctuation; $k = \frac{v_t - v_L}{v_L}$

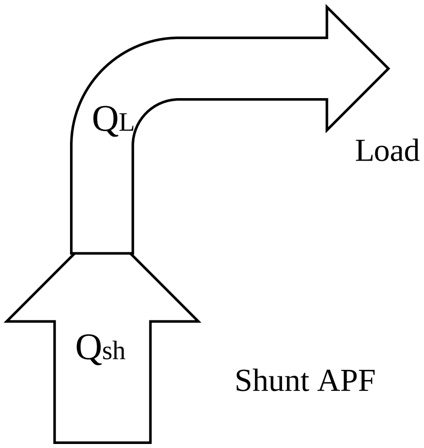
Circuit Diagram of UPQC is given in fig. 3.5. UPQC is used to eliminate harmonics present in current and distortions of voltage and is used for reactive power compensation. In UPQC series APF is used as voltage source inverter to compensate for voltage distortions and make voltage at load side completely balanced and sinusoidal. Series APF injects a voltage which is difference of source voltage and perfectly balanced load voltage. Shunt APF is used as to eliminate harmonics present in load current so that source current is completely sinusoidal and also used for compensation of reactive power. Shunt APF is also used to maintain value of DC link capacitor constant.

Case 1

During normal operations when UPQC is disconnected from supply the reactive power is completely supplied from the main source. But when UPQC is joined with the system than the reactive power is supplied with the Shunt APF. Shunt APF provides reactive power to the load and there is no burden on main supply. Series APF has no relation with reactive power demand of load.



(a) Without UPQC



(b) With UPQC having Shunt APF

Fig.3.6 (a)-(b) Reactive power flow

Here Q_s = reactive power of source

Q_L= reactive power of load

Q_{sh} = reactive power of shunt APF

Case 2

Here k<0, that is $v_t < v_L$, in this case series APF is used to supply real power to load. This is the voltage dip (sag) condition here i_s will be higher than normal current. In this required power is taken from source at increased current so that power will be balanced in the network and DC capacitor value should be at desired level. Here series injected power will be positive.

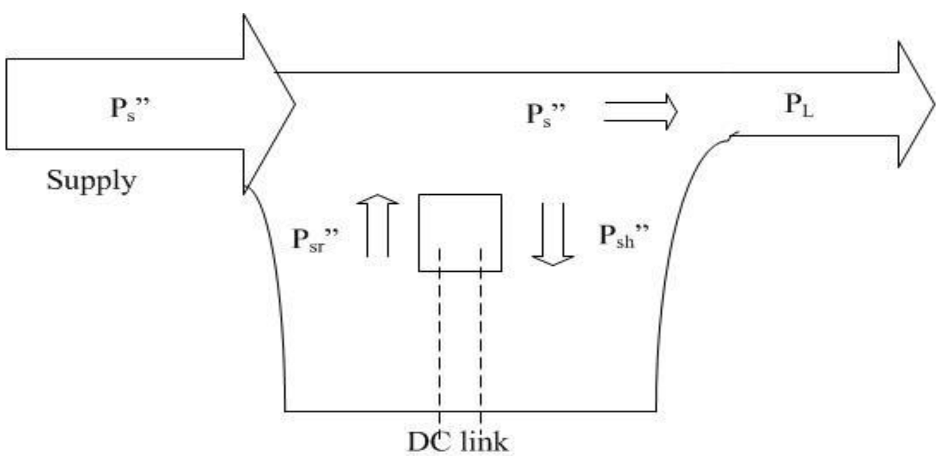


Fig. 3.7 Real power flow during Voltage dip (sag) condition

Here P_s'' = power supplied form the source to load during voltage sag condition.

P_{sr}'' = series APF injected power

P_{sh}'' = shunt APF absorbed power during voltage dip condition

$P_{sr}'' = P_{sh}''$

From source to Shunt APF the real power flows, first real power flow from source to shunt APF and then from shunt APF to series APF through DC link capacitor and from Series APF to load. So load will get desired power during voltage sag condition. In this case the real power absorbed by shunt APF from source is equal to real power supplied by series APF to load. It is given in fig. 3.7.

Case 3

When k>0, that is $v_t > v_L$. Here Series APF absorbs more power from source here P_{sr}'' is negative. This happens during voltage rise (swell) condition. Here i_s will be lesser than normal current. As v_s is increased DC link capacitor voltage increases. Shunt APF lessen the current from supply so that the DC link voltage remains constant. UPQC gives extra amount of power to system. Given in fig. 3.8

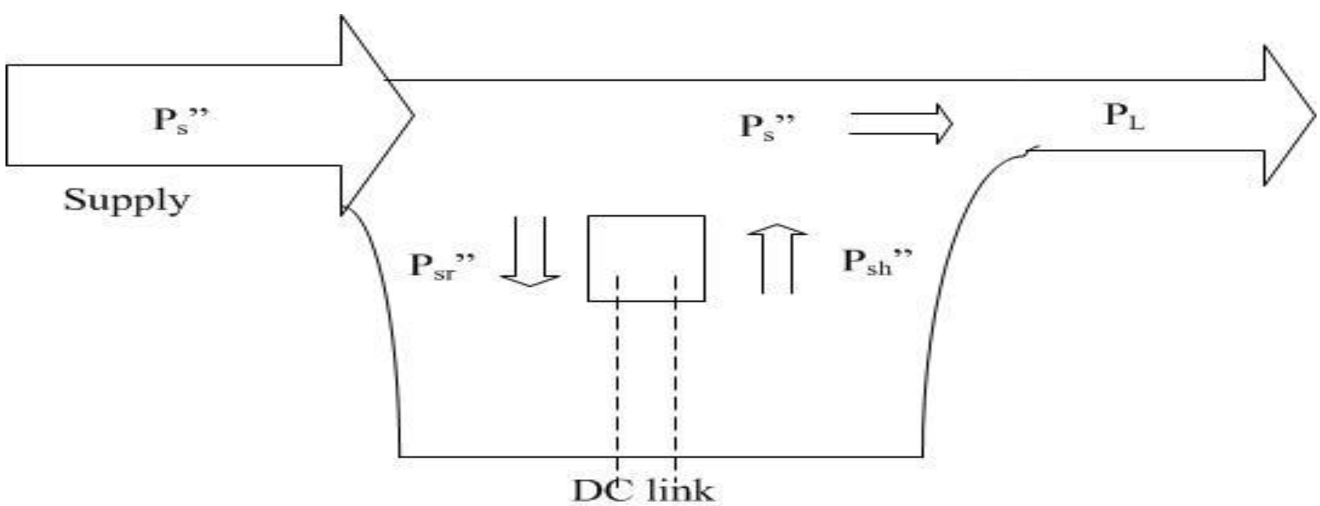


Fig. 3.8 Real power flow during voltage rise condition

Here P_s'' = power supplied form the source to load during voltage rise condition.

P_{sr}'' = series APF injected power; such that P_s''- P_{sr}''=required voltage by load during normal condition

P_{sh}'' = shunt APF delivered power during voltage rise condition

$P_{sr}'' = P_{sh}''$

Case 4

If k=0, that is $v_t = v_L$. In this case no real power flow through UPQC and it is normal condition of operation. Given in fig. 3.9

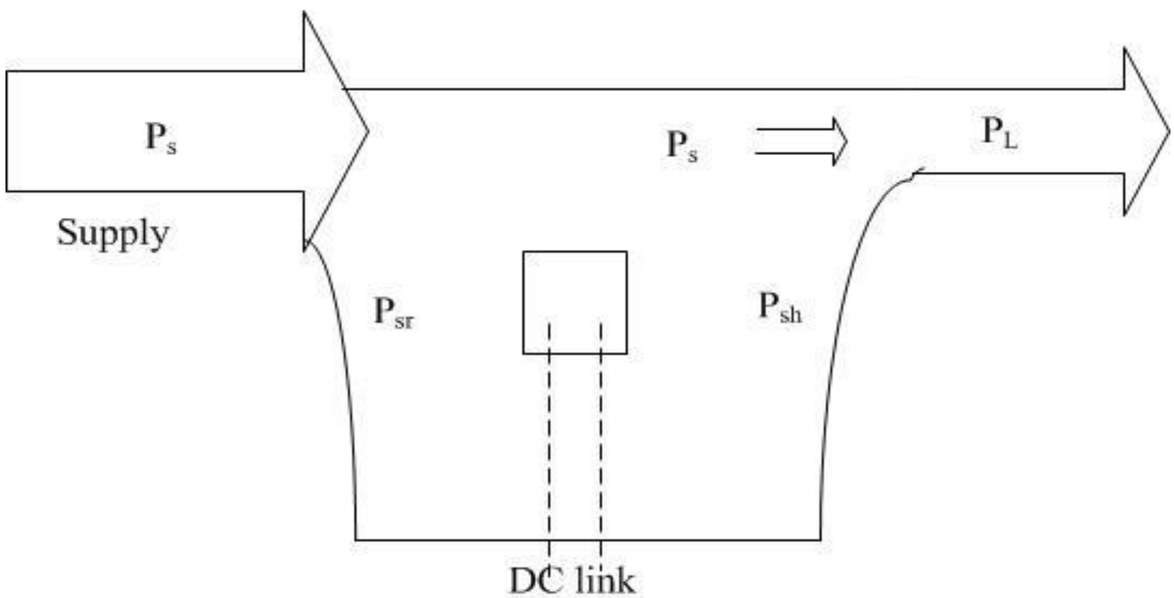


Fig 3.9 The real power flow in normal condition

3.4 Shunt Active Power Filter

Active power filters are devices which generates the same amount of harmonics which are generated by load but at 180^0 phase shifted. Active power filters are devices such as amplifiers etc. Shunt APF injects the compensating current in the line at the point of common coupling (PCC) so that the current at source sides become completely sinusoidal and free from distortions. Generally due to presence of non-linear load there is harmonics & distortions in load current due to which source current also get effected and source current becomes non-sinusoidal and distorted. So to remove this non-sinusoidal behavior of source current we use Shunt APF which provides the compensating current which is same as harmonic generated by load but 180^0 phase shifted and this compensating current is given at PCC which helps in removing distortions from source current and makes source current completely sinusoidal. Shunt APF is also used for reactive power compensation & it also removes all problems which arises due to current harmonics.

The control scheme used in Shunt APF is instantaneous reactive power theory also known as “p-q theory”. p-q theory is used to generate the reference current and this reference current is given to Hysteresis current controller along with compensating current (actual output current) of Shunt APF. Hysteresis current controller is used to generate gating signal which is then given to voltage source inverter.

3.4.1 Block diagram of shunt APF

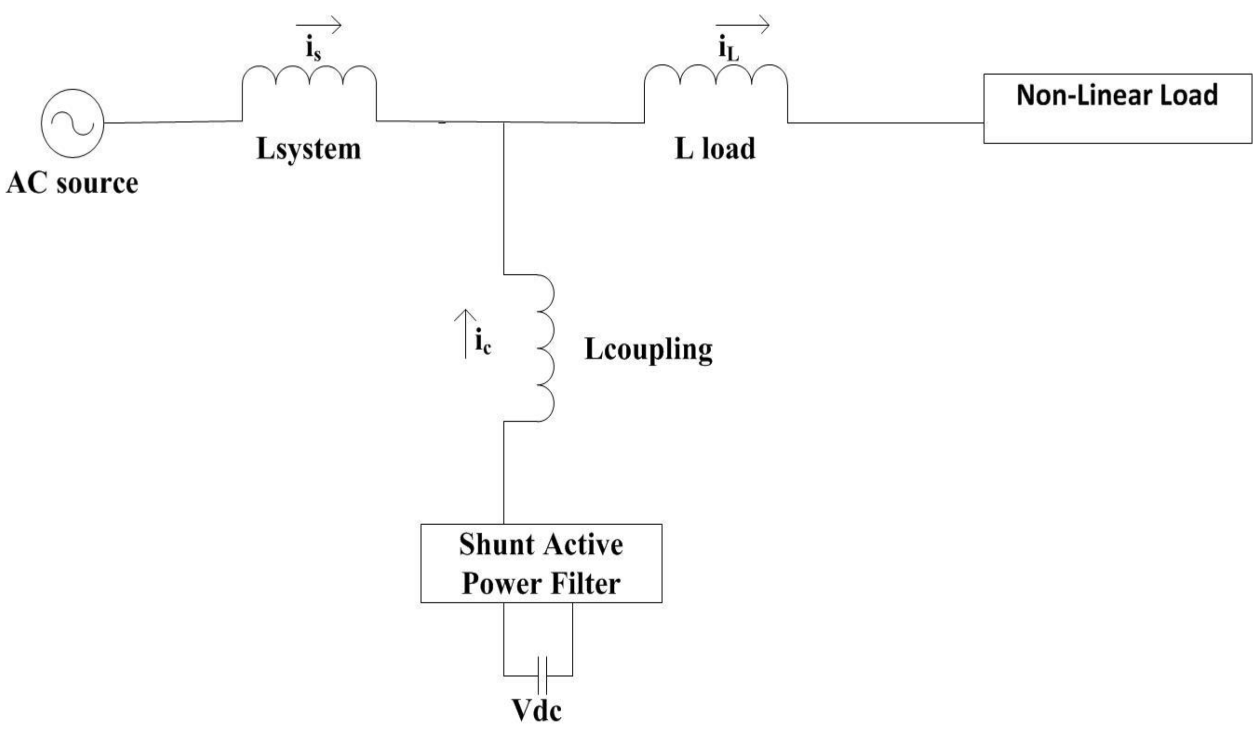


Fig 3.10 Basic control design of shunt APF

In Fig.3.10 given i_s=source current, i_c=compensating current, i_L= load current, V_{dc}= voltage across capacitor

3.4.2 Basic Structure of Shunt APF

Basic structure of shunt APF consists of:-

- **(i)** **DC capacitor:-** It is an energy storage device which provide real power difference between source and load during transient periods.
- **(ii)** **Voltage source inverter:-** VSI is a solid state device like IGBT, GTO etc. It is used to inject compensating current so that the harmonics present in the load current are removed and harmonics doesn't affect source current. And the current taken from source is completely sinusoidal. The PWM signal is given to VSI for its operation.
- **(iii)** **Hysteresis Current Controller:-** Hysteresis current controller is used to generate PWM signal for operation of VSI. The PWM signal is obtained by the error which we get from comparing the reference current with the actual current.
- **(iv)** **PI controller:-** PI controller is used to reduce steady state error. IT is also used to calculate P_{loss}.

3.4.3 Steps for controlling shunt APF

(i) Generation of reference compensating current

(ii) Generation of gating signal by hysteresis current controller

3.4.4 Control scheme of shunt APF

Control pattern used in shunt APF is instantaneous reactive power theory which is also known as "p-q theory". It was introduced by Akagi et al in 1983. The instantaneous reactive power theory is based on time domain transformations, here abc phases are transformed into $\alpha\beta 0$ coordinates. The coordinate 0 corresponds to a zero sequence component. "p-q theory" corresponds to a algebraic transformations which is known as Clarke's transformation. Advantages of "p-q theory" it is simple as it only requires algebraic operations. It is applicable for steady state and transient state operation. In this theory abc phases are converted to $\alpha\beta 0$ are given below:-

Instantaneous reactive power theory

Clarke's transformation is given below

$$\begin{bmatrix} \mathbf{v_0} \\ \mathbf{v_\alpha} \\ \mathbf{v_\beta} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{pmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{pmatrix} \begin{bmatrix} \mathbf{v_a} \\ \mathbf{v_b} \\ \mathbf{v_c} \end{bmatrix} \tag{3.3}$$

$$\begin{bmatrix} \mathbf{i_0} \\ \mathbf{i_\alpha} \\ \mathbf{i_\beta} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{pmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{pmatrix} \begin{bmatrix} \mathbf{i_a} \\ \mathbf{i_b} \\ \mathbf{i_c} \end{bmatrix} \tag{3.4}$$

Inverse Clarke's transformation is given

$$\begin{bmatrix} \mathbf{v_a} \\ \mathbf{v_b} \\ \mathbf{v_c} \end{bmatrix} = \sqrt{\frac{2}{3}} * \begin{pmatrix} \frac{1}{\sqrt{2}} & 1 & 0 \\ \frac{1}{\sqrt{2}} & -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ \frac{1}{\sqrt{2}} & \frac{1}{2} & -\frac{\sqrt{3}}{2} \end{pmatrix} * \begin{bmatrix} \mathbf{v_0} \\ \mathbf{v_\alpha} \\ \mathbf{v_\beta} \end{bmatrix} \tag{3.5}$$

$$\begin{bmatrix} \mathbf{i_a} \\ \mathbf{i_b} \\ \mathbf{i_c} \end{bmatrix} = \sqrt{\frac{2}{3}} * \begin{pmatrix} \frac{1}{\sqrt{2}} & 1 & 0 \\ \frac{1}{\sqrt{2}} & -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ \frac{1}{\sqrt{2}} & \frac{1}{2} & -\frac{\sqrt{3}}{2} \end{pmatrix} * \begin{bmatrix} \mathbf{i_0} \\ \mathbf{i_\alpha} \\ \mathbf{i_\beta} \end{bmatrix} \tag{3.6}$$

For a three phase three wire system the neutral/ ground is neglected so there is no zero sequence component

Clarke's transform

$$\begin{bmatrix} v_\alpha \\ v_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} * \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} \tag{3.7}$$

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} * \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \tag{3.8}$$

Inverse Clarke's transform

$$\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 0 \\ -1/2 & \sqrt{3}/2 \\ -1/2 & -\sqrt{3}/2 \end{bmatrix} * \begin{bmatrix} v_\alpha \\ v_\beta \end{bmatrix} \tag{3.9}$$

$$\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 0 \\ -1/2 & \sqrt{3}/2 \\ -1/2 & -\sqrt{3}/2 \end{bmatrix} * \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \tag{3.10}$$

By Clarke's transform we have converted the abc phase into $\alpha\beta0$ coordinates and by inverse Clarke's transform $\alpha\beta0$ coordinates to abc phases. In this case the voltages are source voltage and currents are load currents.

Now eq^{n} (3.11) will show the separation of real power and imaginary power from apparent power

$$\begin{bmatrix} p \\ q \end{bmatrix} = \begin{bmatrix} v_\alpha & v_\beta \\ -v_\beta & v_\alpha \end{bmatrix} * \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \tag{3.11}$$

Real/active power is $(p) = \bar{p} + \tilde{p}$ (3.12)

Reactive/imaginary power $(q) = \bar{q} + \tilde{q}$ (3.13)

Here the $\bar{p}$ denotes fundamental component of real power i.e direct component of instantaneous real power and $\tilde{p}$ denotes the alternating component of real power. And $\bar{q}$ denotes the fundamental i.e. direct component of instantaneous imaginary power and $\tilde{q}$ denotes the alternating component of imaginary power. The direct components have the fundamental component of voltages and current & alternating component contains harmonic contents of voltage and current. In Shunt APF compensation of reactive power is done and harmonic contents of real power is removed. Reference Compensation current in $\alpha - \beta$ cordinates of shunt APF is found in eq^{n} (3.14) . Here no p_0 zero sequence power will be there as it is three phase three wire system.

$$\begin{bmatrix} i^*_{c\alpha} \\ i^*_{c\beta} \end{bmatrix} = \frac{1}{v_\alpha^2+v_\beta^2}\begin{bmatrix} v_\alpha & v_\beta \\ -v_\beta & v_\alpha \end{bmatrix}\begin{bmatrix} -\tilde{p}+\overline{p_{loss}} \\ \overline{q} \end{bmatrix} \tag{3.14}$$

A $\overline{p_{loss}}$ is calculated by using DC capacitor , a certain reference voltage is kept for capacitor this reference capacitor voltage is compared with actual DC voltage across capacitor and is given to PI controller for calculation of $\overline{p_{loss}}$. The gain of PI controller is kept proper, it is used to minimize steady state error.

The eq^n (3.14) is reference compensation current in $\alpha - \beta$ coordinates it is converted in reference compensation current in a-b-c axis by inverse Clarke's transformation given in eq^n (3.15)

$$\begin{bmatrix} i^*_{ca} \\ i^*_{cb} \\ i^*_{cc} \end{bmatrix} = \sqrt{\frac{2}{3}}\begin{bmatrix} 1 & 0 \\ -1/2 & \sqrt{3}/2 \\ -1/2 & -\sqrt{3}/2 \end{bmatrix} * \begin{bmatrix} i^*_{c\alpha} \\ i^*_{c\beta} \end{bmatrix} \tag{3.15}$$

3.4.5 Flow chart of Shunt APF control technique

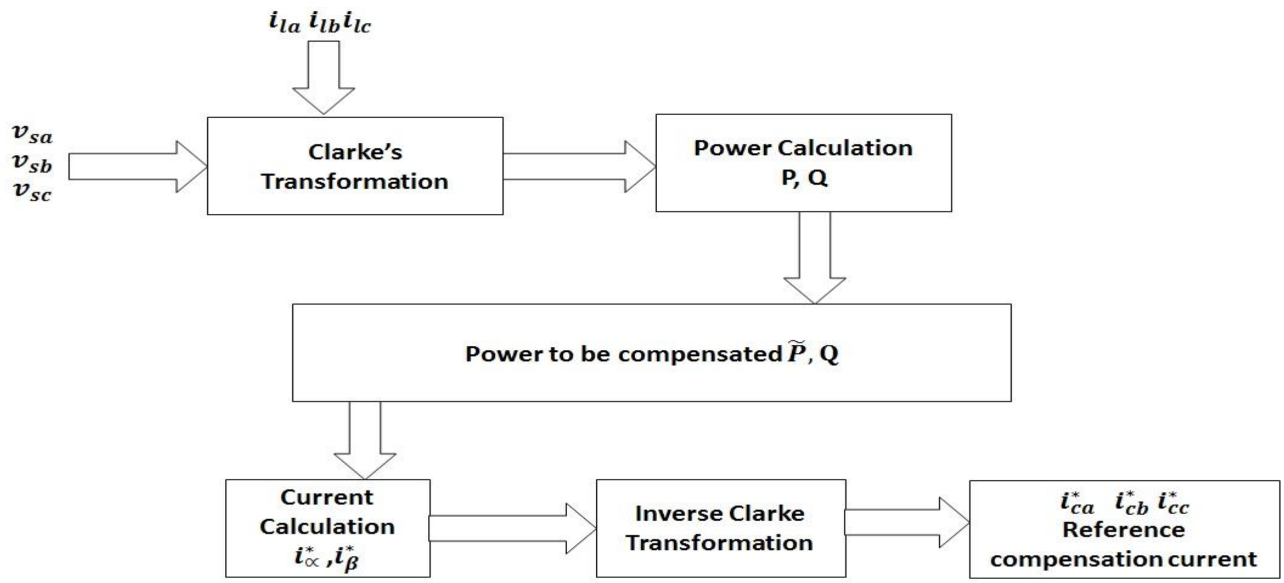


Fig. 3.11 Flow chart of shunt APF control technique

As shown in Fig.3.11. Here source voltages and load currents are taken and it is converted from $a - b - c$ phases to $\alpha - \beta - 0$ cordinates. This conversion is known as Clarke's transformation. After that power calculation is real power and imaginary power is calculated. After that power which is to be compensated is found out. The power loss across DC capacitor should also be found out. It is found with the help of PI controller. Gain of PI controller is kept proper. Power which is to be compensated are harmonic component of real power and whole imaginary power. Then after this current is calculated in $\alpha - \beta$ coordinates. This currents in $\alpha - \beta$ coordinates are transformed into $a - b - c$ axis by inverse Clarke's transformation. This is the reference compensating current. It is given to hysteresis current controller along with shunt APF actual output current. In current calculation low pass filter is used to remove higher order harmonics of power.

3.4.6 Hysteresis Current Controller

Hysteresis controller is used as it is simple, it has fast transient response, it enhances stability,& has good accuracy. Hysteresis current controller is used for producing switching signal by comparing the error present in the current in a fixed tolerance band. Here comparison is done between the actual current & reference current within a fixed tolerance band. It is different for different phases.

Hysteresis current controller is used to compare current so to generate switching signals for Shunt APF. Here the reference current i_c^* is compared with actual current i_c of shunt APF within a given hysteresis band. A hysteresis band is a boundary of actual current.

When $i_{ca} < (i_{ca}^* - \frac{HB}{2})$ then the upper switch is ON and lower switch is OFF and the current is allowed to decay in phase a it is similar for phase b & c. When $i_{ca} > (i_{ca}^* + \frac{HB}{2})$ then upper switch is OFF and lower switch is ON. Given in Fig. 3.12

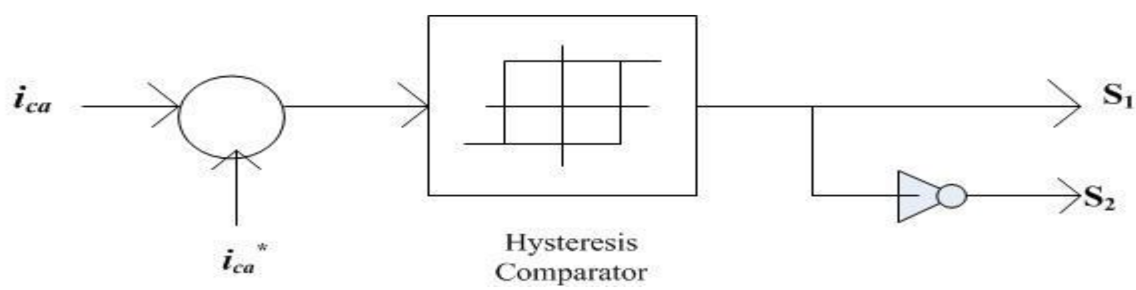


Fig. 3.12 Hysteresis current controller

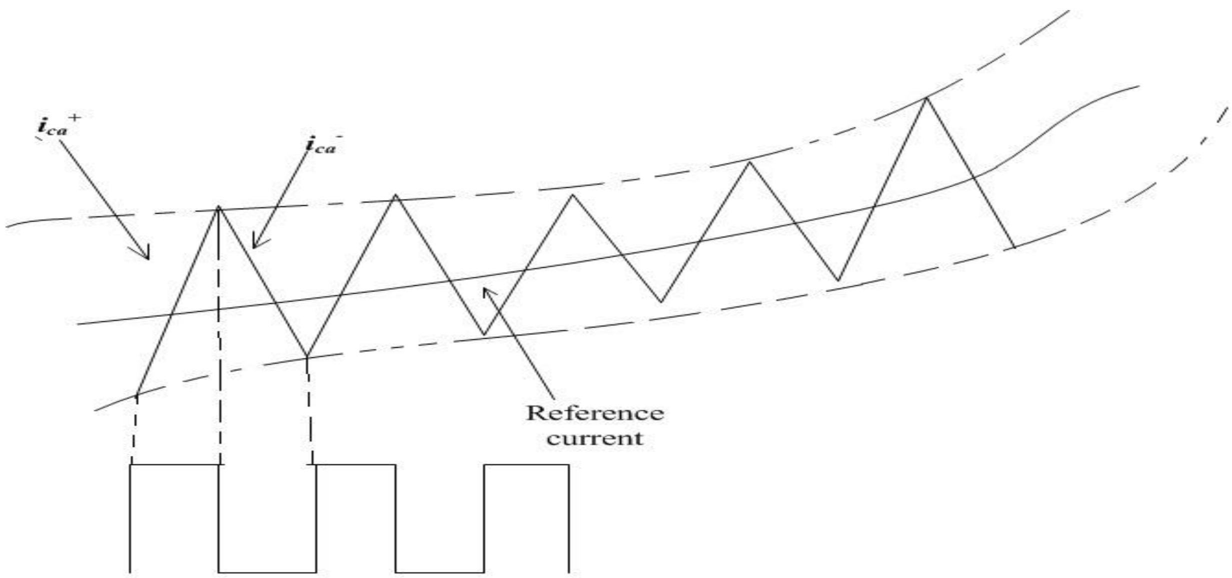


Fig. 3.13 Principle of hysteresis current controller

The fig.3.13 shows principle of hysteresis controller here reference current is the middle one & triangular waveform is actual current. The border of actual current is the hysteresis band.

3.4.7 PI controller

PI controller is mainly used to reduce the steady state error. It is also used to find out the power loss p_{loss} which is used in real power calculations. Power Loss can also be filter loss.

3.4.8 DC voltage regulator

It consists of a energy storage element such as capacitor. It is used to provide real power difference between source and load during transient period. DC capacitor value should be equal to reference value but due to changes in load condition its value decreases from reference value.

3.5 Series Active Power Filter

A series active power filter is equipment which is used to mitigate the problems which are caused due to voltage distortions and voltage unbalance in source voltage. The voltage distortions and unbalance means voltage dip, voltage rise, voltage fluctuations, voltage flicker these are removed from the source voltage by means of Series APF. A series APF injects a voltage component in series with supply voltage and removes harmonic component and distortions, unbalance present in voltage waveform. The series APF is used to remove all these voltage problems from supply voltage and make load voltage perfectly balanced and regulated. Series APF is connected in series with transmission line with a series transformer. The turns ratio of series transformer should be proper so that the injected voltage should come properly. Here three phase reference voltage is calculated by transforming $a-b-c$ to $d-q-0$ reference frame and again by transforming $d-q-0$ to $a-b-c$ frame. After that the reference voltage is given to hysteresis voltage controller with the actual output voltage of series APF (voltage we got across series transformer) and the PWM signal is generated which is given to voltage source inverter. The DC voltage is given across VSI so to get real power difference between source and load.

3.5.1 Block Diagram of Series APF

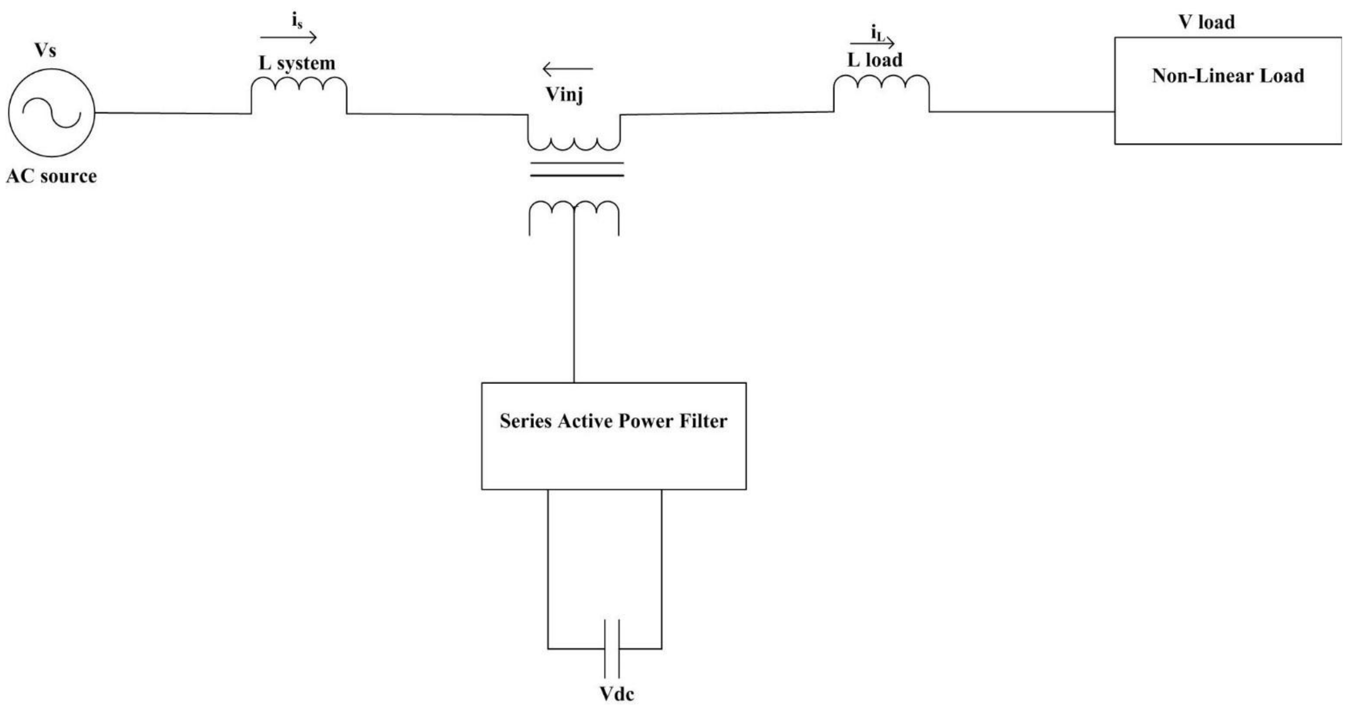


Fig. 3.14 Basic Control design of Series APF

As given in Fig.3.14, here i_s= source current

v_{inj}= injected voltage across transformer

i_L= load current

V_{dc}= dc voltage

3.5.2 Basic structure of series APF

The basic structure of series APF contains

(i) Series Transformer
(ii) DC Voltage regulator
(iii) Voltage source inverter
(iv) Hysteresis Voltage controller

3.5.3 Steps for controlling series APF

(i) Generation of reference compensating voltage

(ii) Comparing reference compensating voltage with actual compensating voltage in hysteresis voltage controller and generating PWM signal for voltage source inverter.

3.5.4 Control scheme of series APF

The control pattern of series APF is based on Park's transformation or $dq0$ transformation. Here we compared the reference voltage with actual output voltage of series APF. The supply voltage is first converted into $dq0$ coordinates form abc phases. Then this output voltage is compared with input reference voltage which is first converted into dqo coordinates. After comparing this two voltages they are again transformed from dqo coordinates to abc phases. The wt required in converting dqo to abc coordinates or vice versa we get from PLL (phase locked loop). After this the supply voltage is given to PLL and wt is generated. Then this wt along with dqo output voltages are transformed into abc phases which is the reference output voltage. Then this reference output voltage (v_c^*) is compared with sensed series APF output voltage (v_c) in hysteresis voltage controller and PWM signal is generated which is given to VSI. The PLL is a control system that generates an output signal whose phase is related to phase of an input signal. For simplicity zero sequence component is ignored.

The dqo transformation to abc transformation are given below

$$\begin{bmatrix} v_d \\ v_q \\ v_0 \end{bmatrix} = \frac{2}{3}\begin{bmatrix} \sin(\omega t) & \sin(\omega t - \frac{2\pi}{3}) & \sin(\omega t + \frac{2\pi}{3}) \\ \cos(\omega t) & cos(\omega t - \frac{2\pi}{3}) & cos(\omega t + \frac{2\pi}{3}) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix}\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} \quad (3.16)$$

Inverse Park's transform i.e from abc to dqo transform

$$\begin{bmatrix} v_d \\ v_q \\ v_0 \end{bmatrix} = \begin{bmatrix} \sin(\omega t) & \cos(\omega t) & 1 \\ \sin(\omega t - \frac{2\pi}{3}) & \cos(\omega t - \frac{2\pi}{3}) & 1 \\ \sin(\omega t + \frac{2\pi}{3}) & \cos(\omega t + \frac{2\pi}{3}) & 1 \end{bmatrix} \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} \quad (3.17)$$

3.5.5 Flow chart of series APF control technique

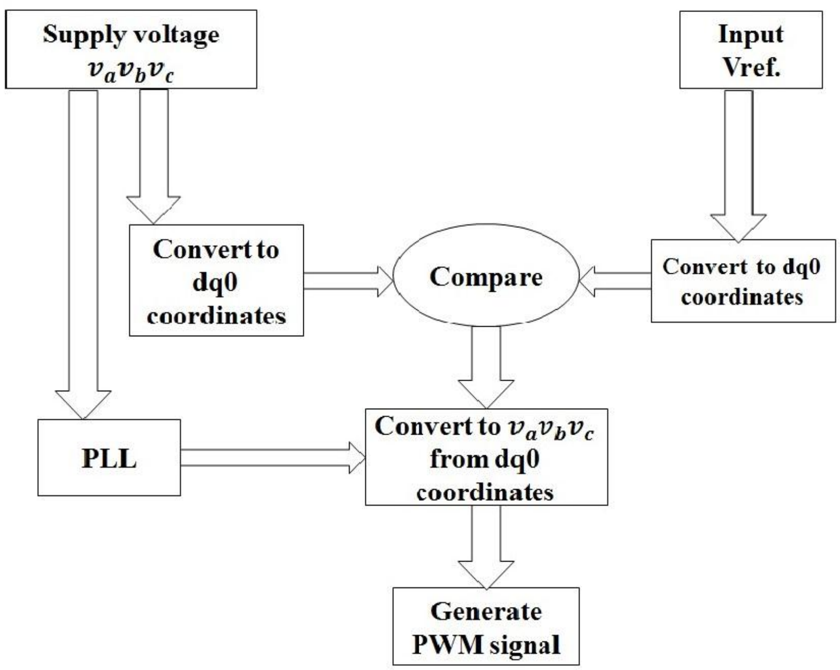


Fig. 3.15 Flow chart of control technique of series APF

The Fig.3.15 shows the Flow chart of control technique of series APF

3.5.6 Hysteresis Voltage Controller

A hysteresis voltage controller is used to generate the PWM signal for VSI. In this the instantaneous value of output voltage or sensed output series APF voltage (Injected voltage, v_c) is compared with the reference voltage v_c^* which is generated by Park's transformation. Hysteresis voltage controller gives output signal to VSI inverter whenever error is generated. Switching occurs whenever output voltage crosses hysteresis band. It is for the phase "a" operation for "b and c" it is same. Whenever $v_{ca} = v_{ca}^* + \frac{HB}{2}$ then upper switch is OFF and lower switch is ON. And $v_{ca} = v_{ca}^* - \frac{HB}{2}$ then upper switch is ON and lower switch is OFF. As shown in Fig.3.16

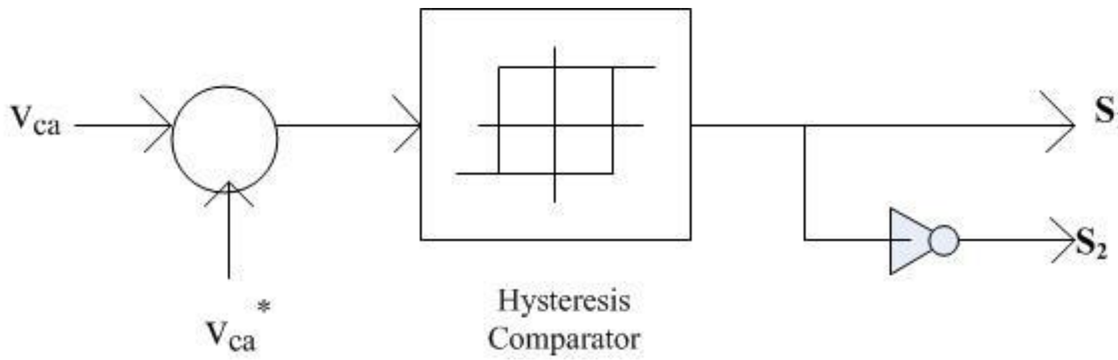


Fig. 3.16 Hysteresis voltage controller

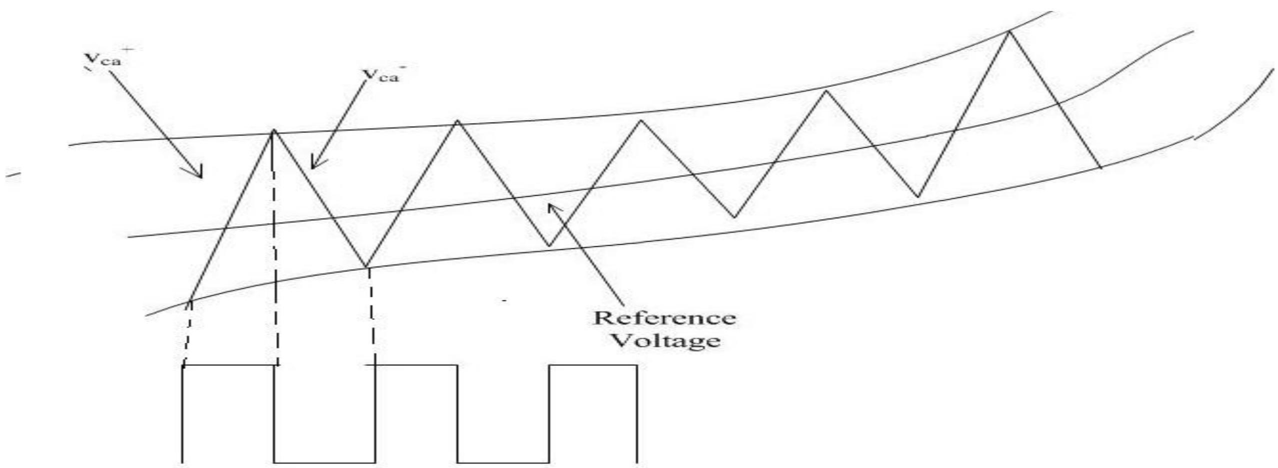


Fig.3.17 Principle of Hysteresis Voltage controller

The fig.3.17 shows the principle of hysteresis controller here reference voltage is the middle one & triangular waveform is actual voltage. The border of actual voltage is the hysteresis band.

3.5.7 Series Transformer

The necessary voltage which is generated by series APF so that the voltage at load side is perfectly balanced and regulated i.e. Sinusoidal is injected into the transmission line with the help of these transformers. The series transformer turns ratio should be suitable so that injected voltage is suitable such that it injects a compensating voltage which will completely make the load side voltage balanced and also it reduces the current flowing through series inverter.

3.5.8 DC voltage regulator

A DC voltage regulator is energy storage component such as capacitor or a battery. It is used to supply DC voltage to VSI. It is also used to provide real power difference between source and load during transient period.

Chapter 4

RESULTS AND DISCUSSIONS

4.1 Introduction

The simulation results are discussed in this chapter. In Shunt APF "p-q theory" and hysteresis current controller was used for getting simulation results. In Series APF "dq0 transformation" and hysteresis voltage controller were used for getting simulation results. After that Shunt APF and Series APF were combined to get simulation results and Combination is known as UPQC.

4.2 Simulation Results of Shunt APF

Shunt APF is used to remove problems due to current harmonics. So it makes current drawn from source completely sinusoidal which is effected by load current harmonics. In Table-4.1 system parameters of shunt APF are given

Table-4.1 System Parameters used for Shunt APF

Supply Voltage	400 V
Line impedance	R_s= 0.01 Ω, L_s= 1 μH
DC Voltage	850 V
DC capacitor	500 μF
Load impedance	R_L=0.0001 Ω, L_L=1 μH
Line frequency	50 Hz

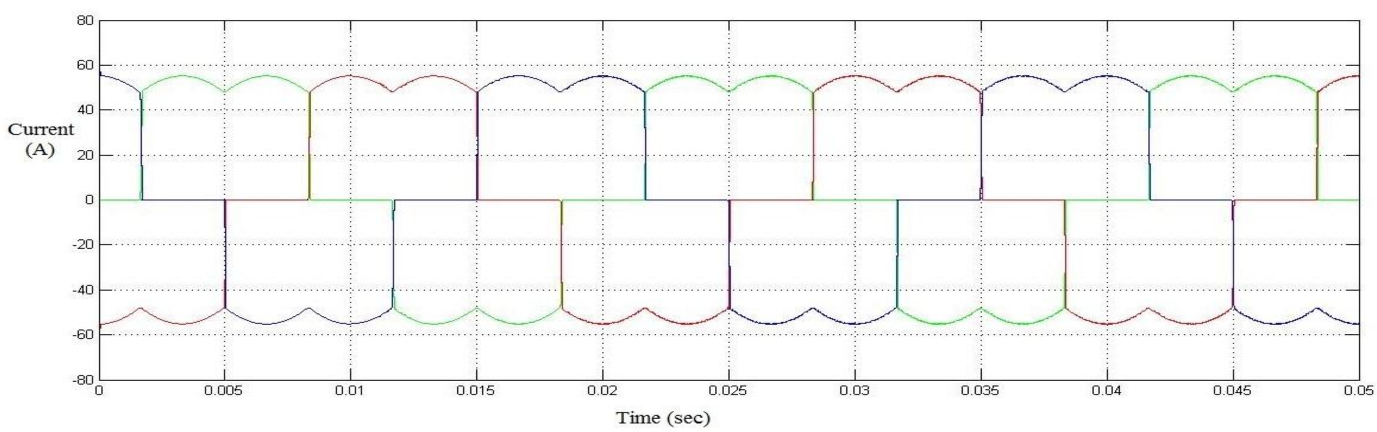


Fig. 4.1 Load current of Shunt APF

In fig.4.1 the waveform of load current of shunt APF is given and they are not sinusoidal due to presence of non-linear loads. This is non-linear waveform. They are Non-linear due to presence non-linear loads like diode etc.

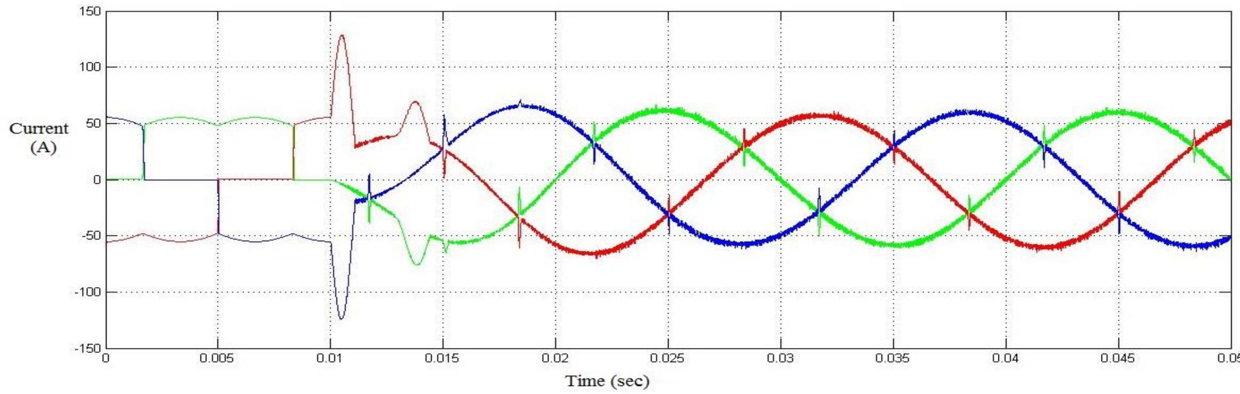


Fig. 4.2 Source current of Shunt APF

Fig. 4.2 shows source current of shunt APF. The source current contains harmonics till 0.01 sec as up to this time shunt APF is not in operation. After 0.01 sec shunt APF starts operating in a system. So after 0.01 sec the harmonics are removed from source current. The time of operation of shunt APF is controlled by circuit breaker.

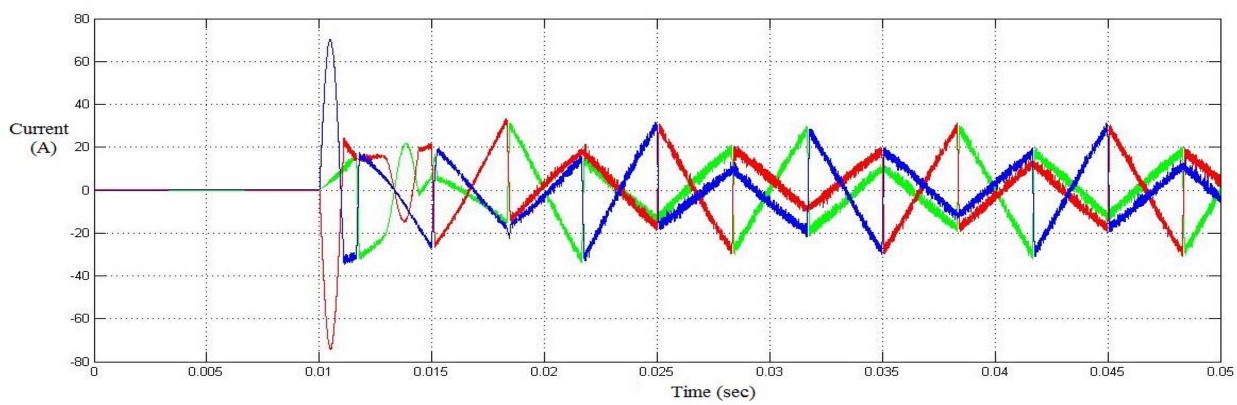


Fig. 4.3 Injected current by Shunt APF

In fig.4.3 the current injected by shunt APF is given the current is injected from 0.01 sec. As shunt APF starts operation from 0.01 sec. After 0.01 sec the source current will become completely sinusoidal.

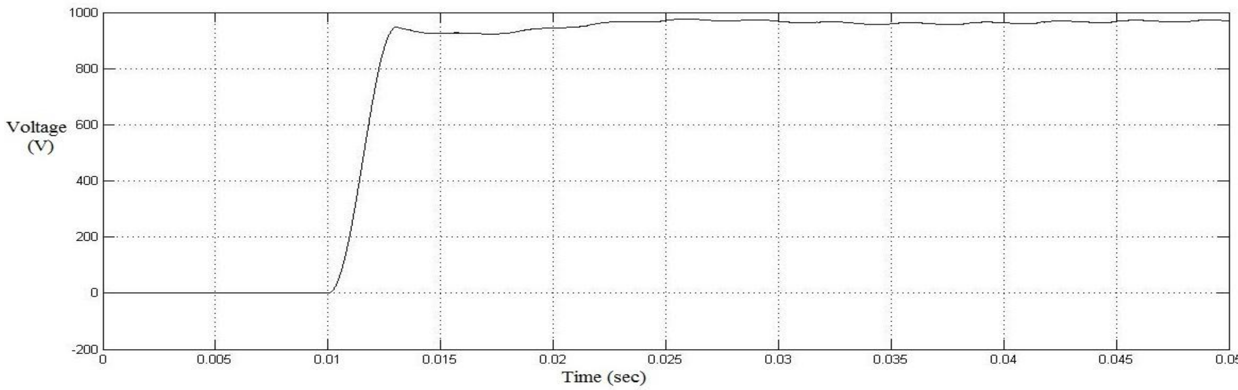


Fig. 4.4 Capacitor Voltage

In Fig.4.4 capacitor voltage is given. After 0.01 sec capacitor voltage rises and become constant. Because after that shunt APF starts operating. And DC capacitor always try to follow reference DC voltage which is 850 V.

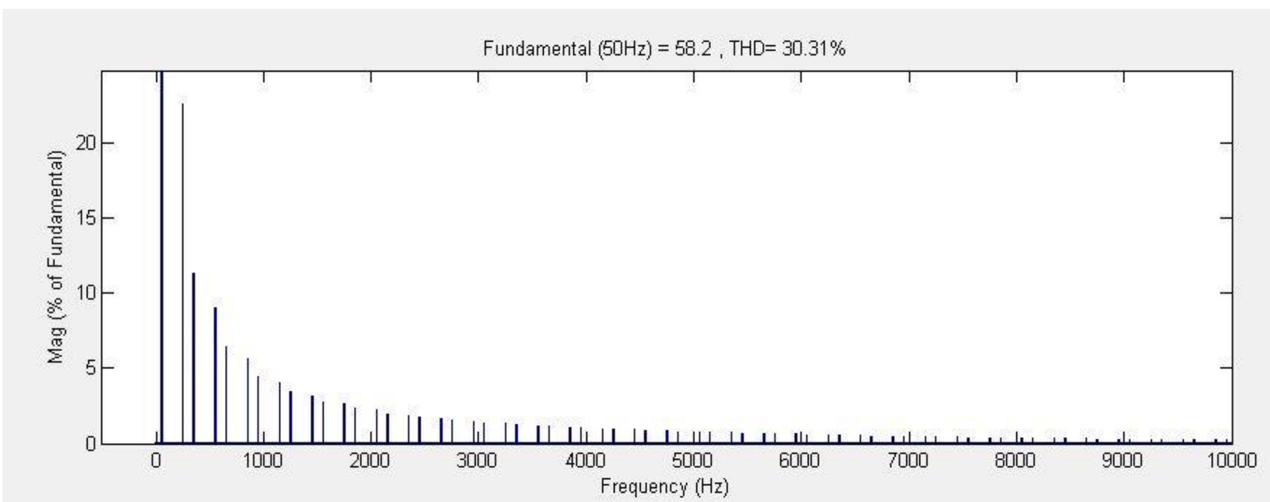


Fig. 4.5 THD of load current of shunt APF

In Fig.4.5 the THD of load current is shown. The THD in load current is 30.31% as the load contains non-linear load.

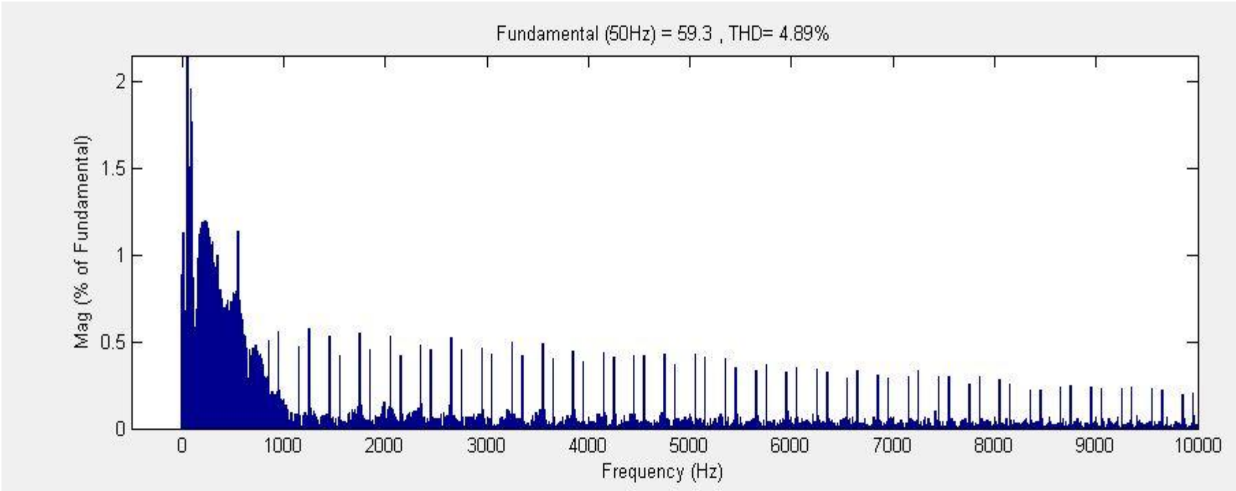


Fig. 4.6 THD of source current after using Shunt APF

In fig.4.6 the THD of source current is shown. The THD in source current is 4.89% after use of shunt APF. So we come to know that after applying Shunt APF the harmonic contents in current are reduced.

4.3 Simulation Results of Series APF

Series APF is used to mitigate all problems related to voltage unbalance and disturbance. It mitigate the voltage unbalance in source voltage i.e. voltage dip/rise so that the load voltage become perfectly balanced and regulated. Table-4.2 shows system parameters of series APF

Table-4.2- System parameters used for series APF

Supply Voltage	326 V
Line Frequency	50 Hz
Line impedance	R_s= 0.1 Ω , L_s =0.1 mH
Load impedance	R_s= 30 Ω , L_s =1 mH
Series Transformer turns ratio	1:1
DC bus voltage	520 V

4.3.1 Voltages across series APF during sag

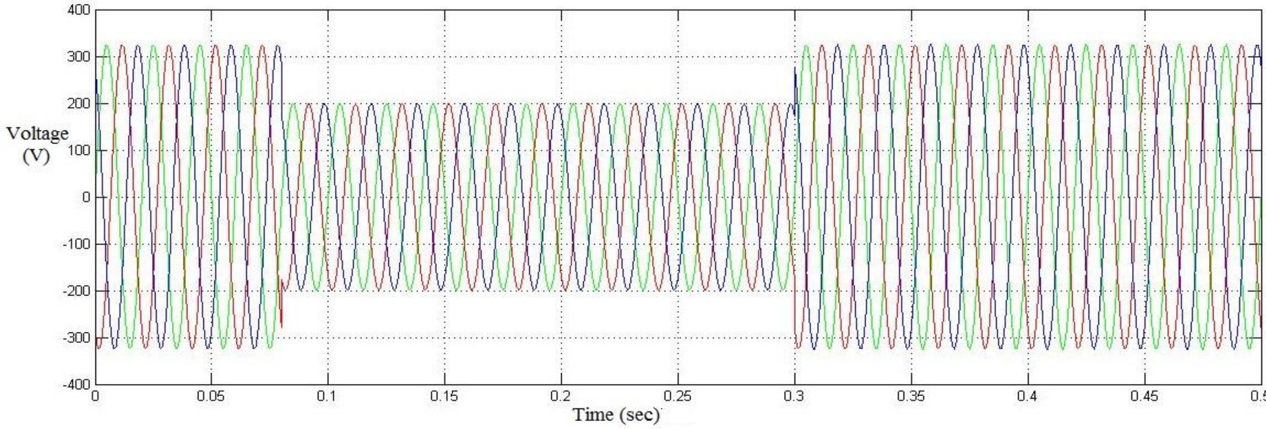


Fig.4.7 Source voltage of series APF during sag

As given in Fig.4.7 it is the source voltage during sag. Sag time interval is 0.08 sec to 0.3 sec. The sag is due to voltage unbalance that may be caused due to faults.

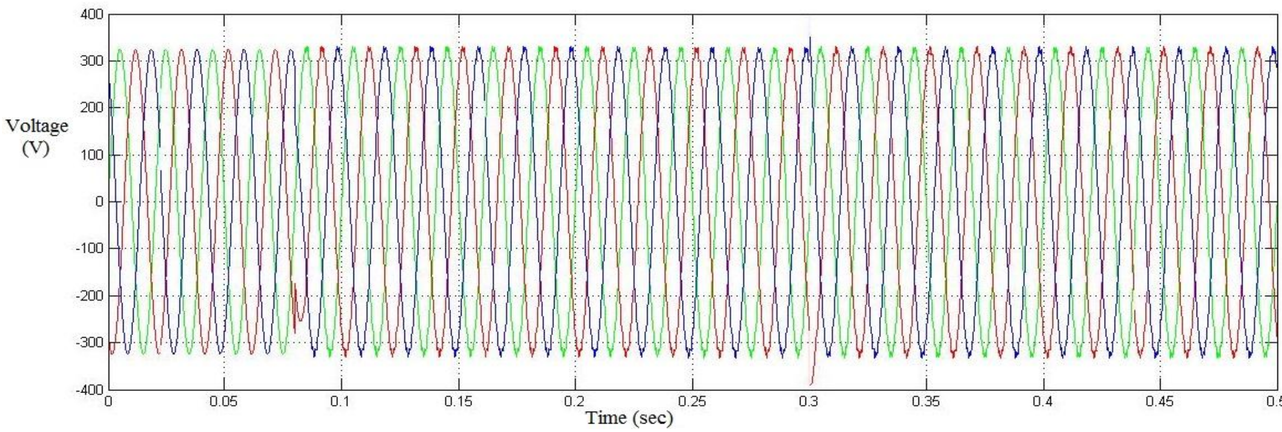


Fig.4.8 Load voltage of series APF during sag

The Fig.4.8 shows the load voltage of series APF that is completely sinusoidal and perfectly balanced. As after application of series APF the load voltage becomes balanced. The sag at time interval 0.08 sec to 0.3 sec are removed by the help of series APF. The load voltage becomes free from all unbalance which was caused due voltage dip.

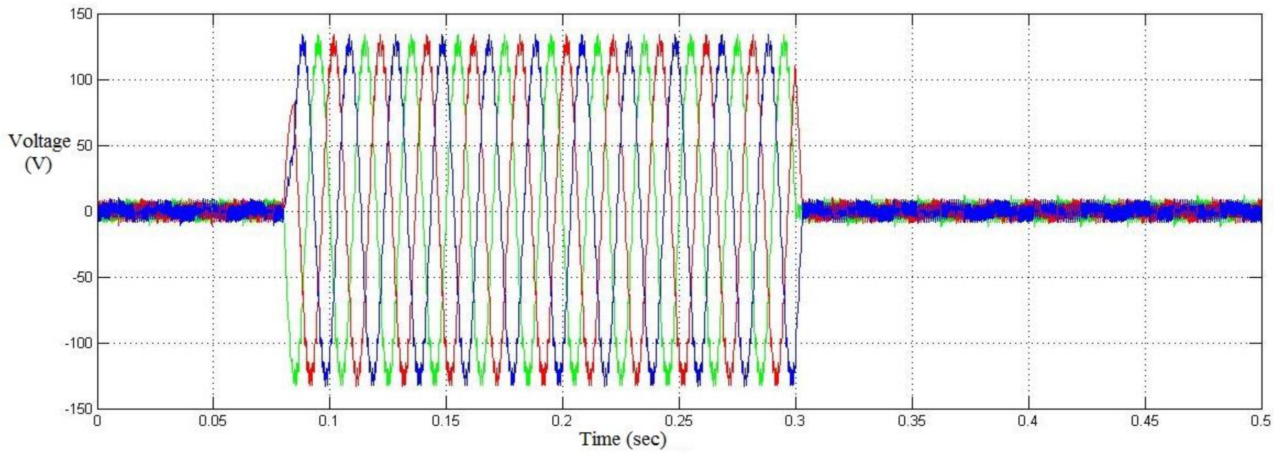


Fig. 4.9 Voltage injected by series APF

In Fig.4.9 the voltage injected by series APF is shown. The injected voltage time interval is 0.08 sec to 0.3 sec. By injecting voltage in this time interval the load side voltage is made completely balanced and sinusoidal.

4.3.2 Voltage across series APF during swell

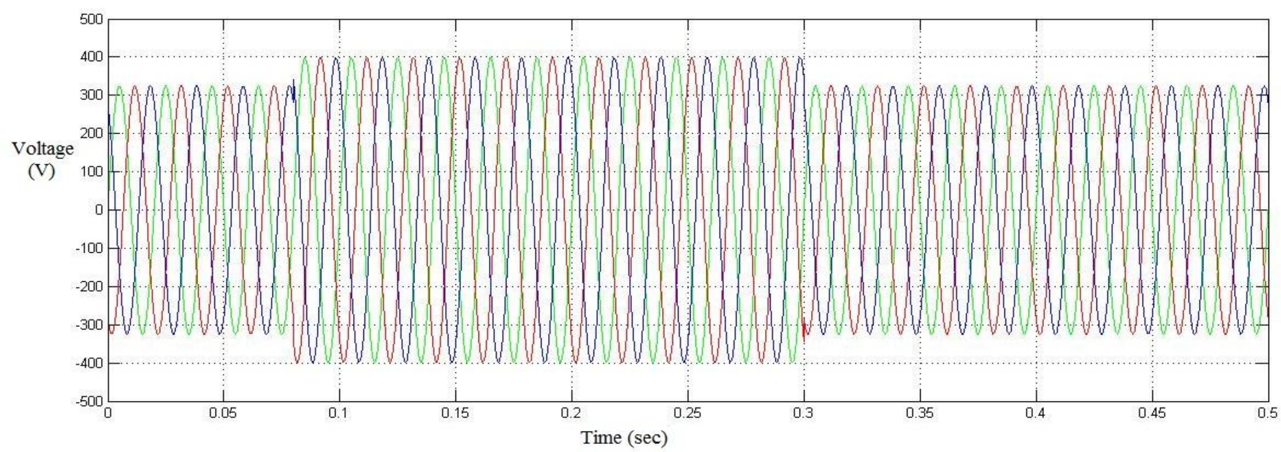


Fig. 4.10 Source voltage during swell of series APF

This fig.4.10 indicates the source voltage of series APF during swell condition. Here the swell is from 0.08 sec to 0.3 sec. There is rise in magnitude of voltage form time interval 0.08 to 0.3 sec. The voltage swell may be due to faults or capacitor switching.

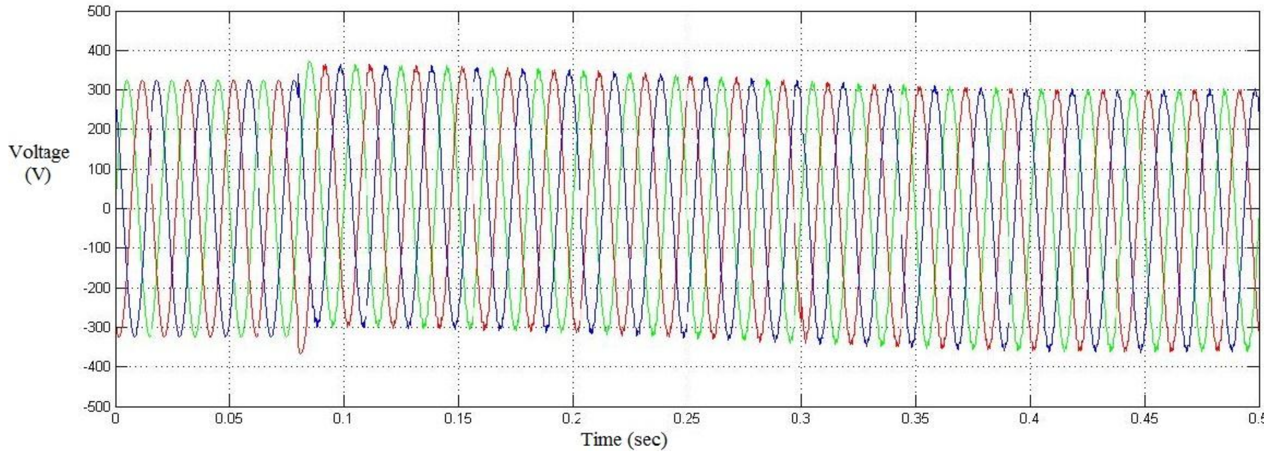


Fig. 4.11 Load Voltage during swell of series APF

In Fig.4.11 the load voltage of series APF during swell is given. Due to operation of series APF the voltage swell from time interval 0.08 sec to 0.3 sec are removed and the load voltage becomes completely balanced. Now the voltage is completely balanced in whole interval of time.

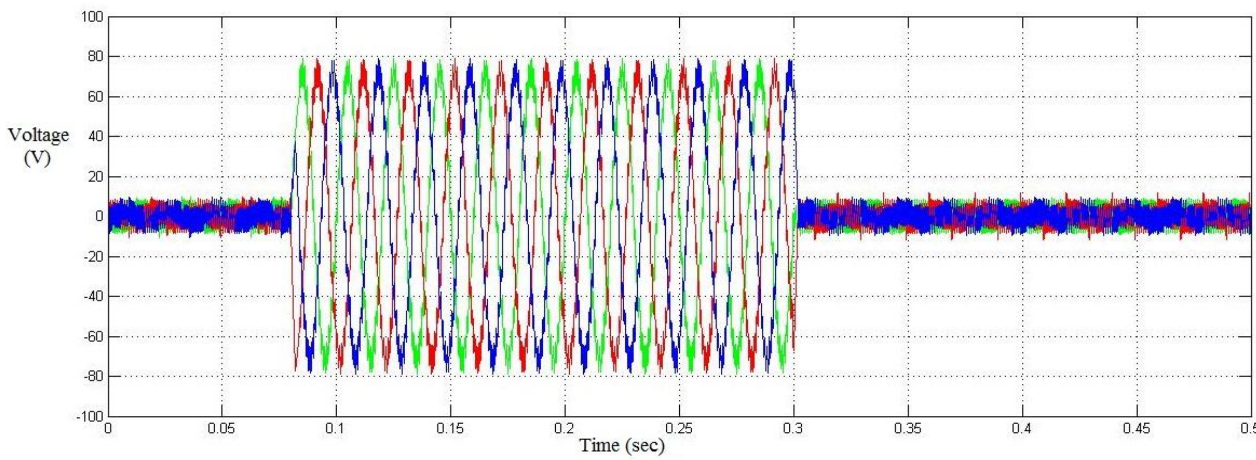


Fig. 4.12 Injected voltage during swell of series APF

Fig.4.12 shows the injected voltage by series APF during swell condition. The voltage is injected in time interval 0.08 sec to 0.3 sec. By injecting this voltage the load voltage across series APF becomes completely regulated.

4.4 Simulation results of UPQC

UPQC is a equipment which is formed by combining series APF and Shunt APF together. UPQC removes both problems which are caused due to voltage and current harmonics. UPQC mitigate the problems of source voltage unbalance and make load side voltage completely balanced and it also mitigate the problems which is caused due to load current harmonics and make current drawn from source completely sinusoidal. In table-4.3 system parameters of UPQC are given

Table-4.3- System Parameters used for UPQC

Supply Voltage	326 V
Line Frequency	50 Hz
Line impedance	R_s=0.01 Ω, L_s=0.01 mH
Series Transformer Turns ratio	1:1
Load impedance	R_L= 30 Ω, L_L= 1 mH
DC Capacitance	2200 μF
DC capacitor voltage	700 V

4.4.1 Current harmonic compensation and voltage sag mitigation

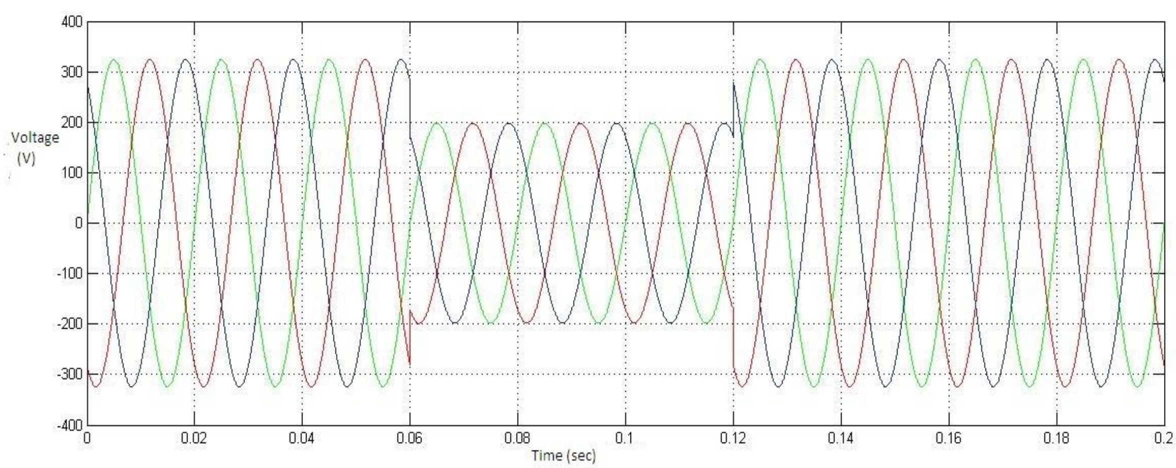


Fig.4.13 Source voltage during sag of UPQC

In fig.4.13 source voltage of UPQC during sag is shown. Total simulation time is 0.2 sec. The voltage dip is from 0.06 sec to 0.12 sec. It is due to presence of faults in the system. Due to sag the voltage from 0.06 sec to 0.12 sec is 200 V.

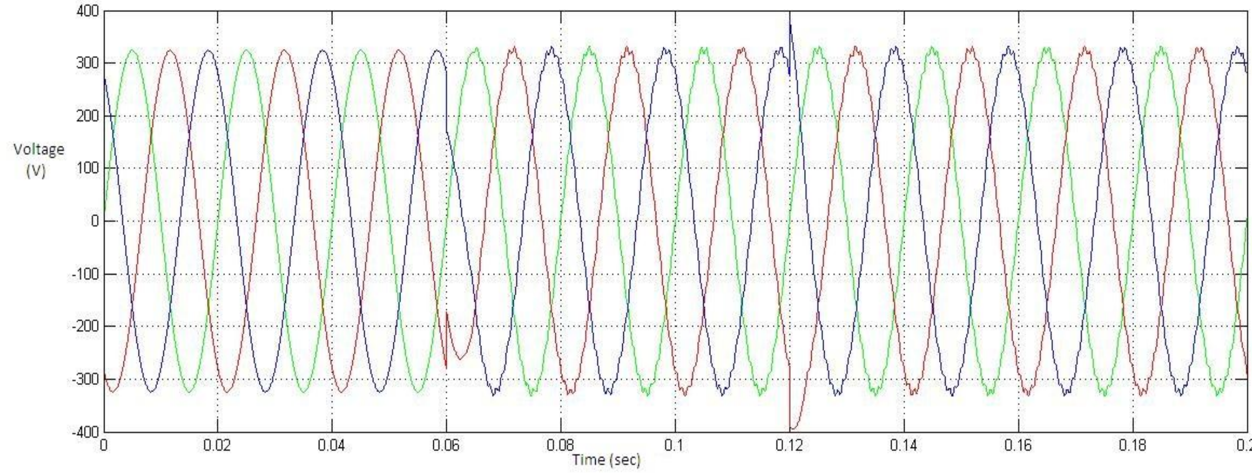


Fig. 4.14 Load voltage during sag after application of UPQC

In Fig.4.14 load voltage of UPQC is shown. After operation of UPQC the sag from time 0.06 sec to 0.12 sec is removed. UPQC removes the voltage sag problems. The total load voltage becomes sinusoidal and gains its original magnitude which is 326 V.

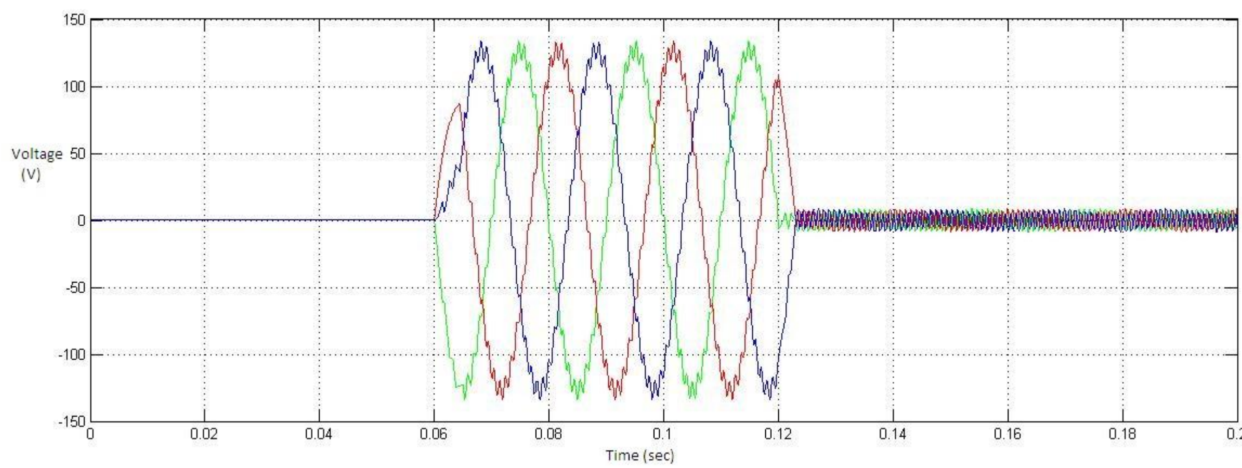


Fig. 4.15 Injected Voltage of UPQC during sag

Fig.4.15 shows the injected voltage of UPQC during sag. The voltage is injected form 0.06 sec to 0.12 sec so that the load voltage becomes completely balanced.

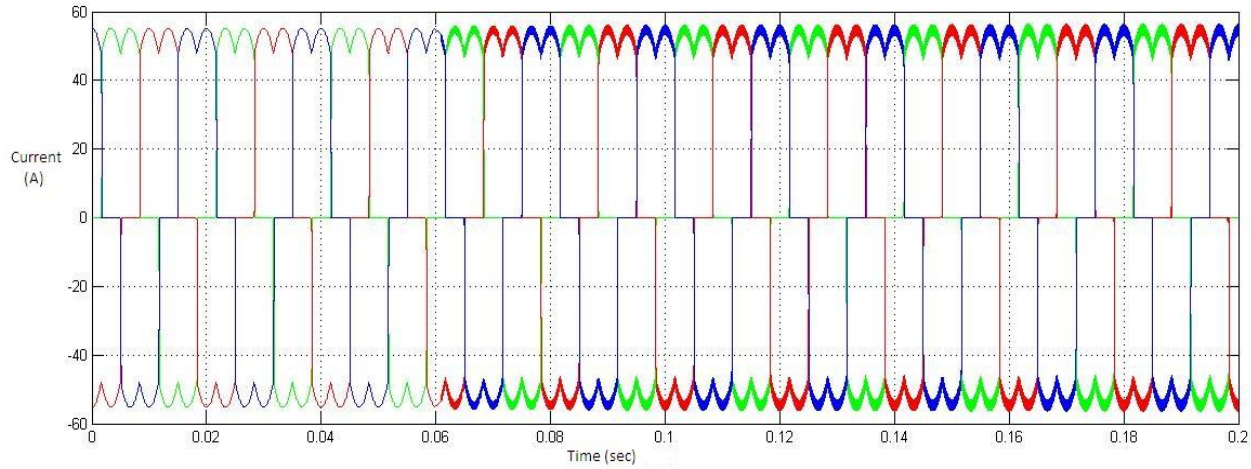


Fig. 4.16 Load current of UPQC during sag

In Fig.4.16 load current of UPQC during sag is shown. The load current of UPQC is contains harmonics and is non-linear due to presence of non-linear load.

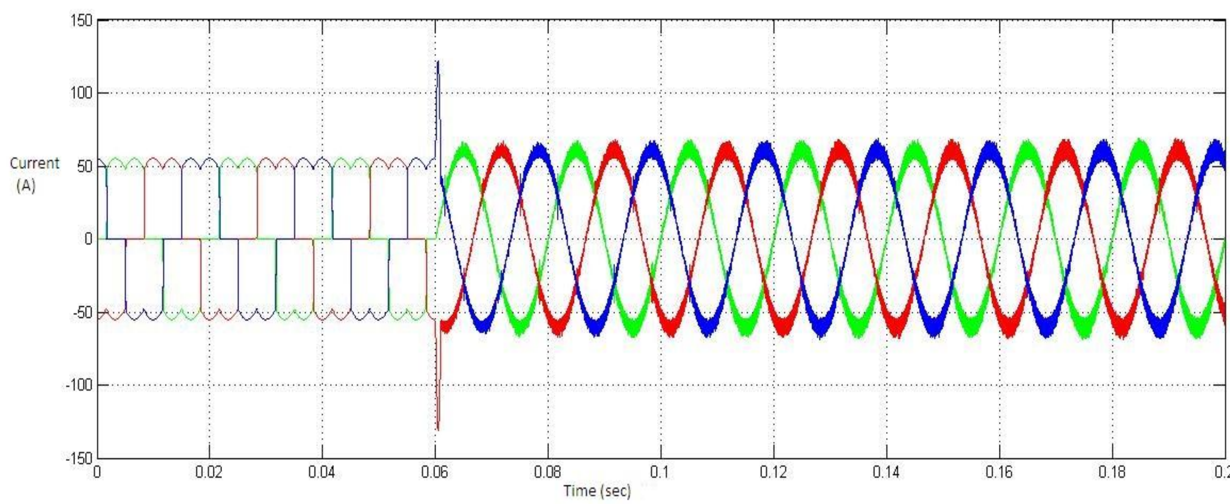


Fig. 4.17 Source current during sag after operation of UPQC

Fig. 4.17 shows source current during sag after application of UPQC. The source current of UPQC is sinusoidal and harmonics are removed after 0.06 sec as after that UPQC starts operating. For current compensation the shunt APF part of UPQC operates.

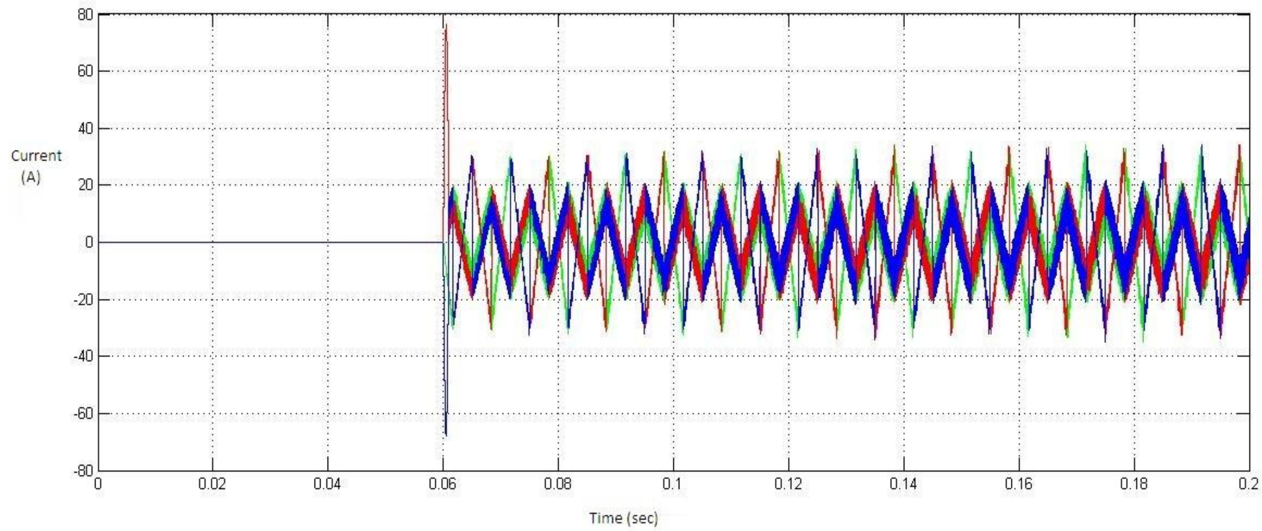


Fig. 4.18 Injected current of UPQC

Fig.4.18 injected current of UPQC is shown during sag condition. For current compensation the current is injected from 0.06 sec as after that tme UPQC starts operating. The start time of operation of UPQC 0.06 sec is adjusted by circuit breaker.

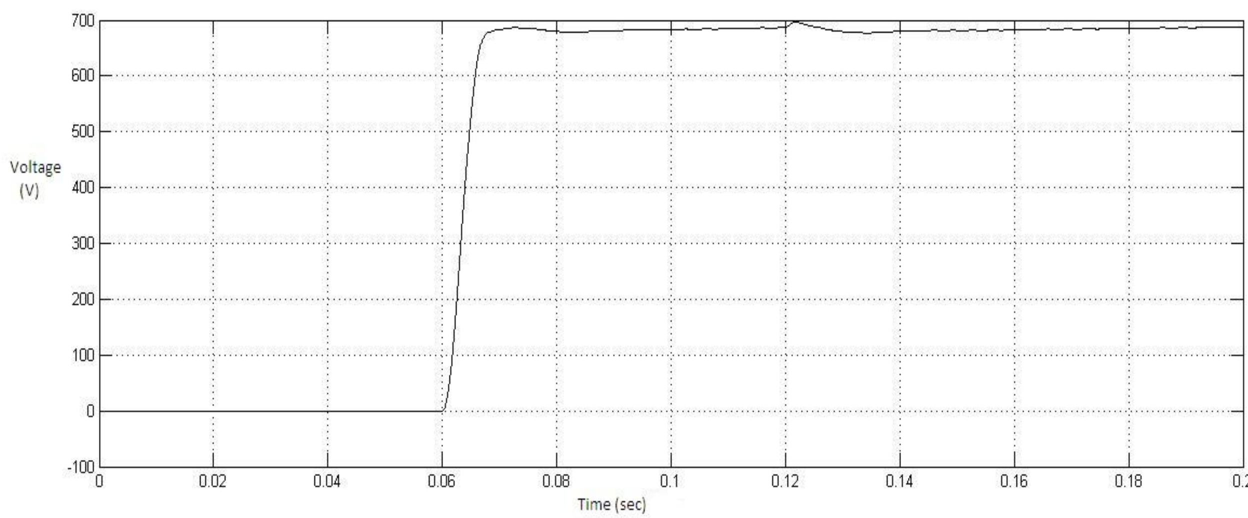


Fig. 4.19 Capacitor Voltage across UPQC

Fig.4.16 shows tha capacitor voltage. The capacitor voltage is kept constant that is 700 V. After time 0.06 sec the capcitor voltage rises and becomes constant. It follows the reference the voltage.

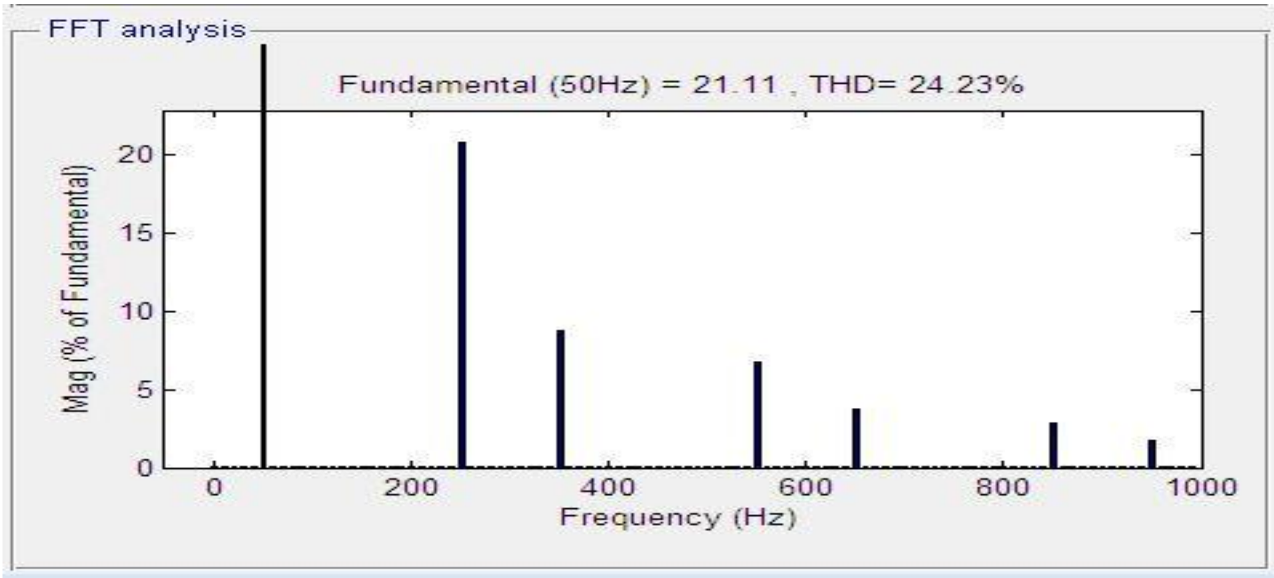


Fig. 4.20 THD of load current of UPQC

Fig.4.20 shows the THD of load current of UPQC. The THD of load current is 24.23% due to non-linear load. As due to non-linear load harmonics are present in load current.

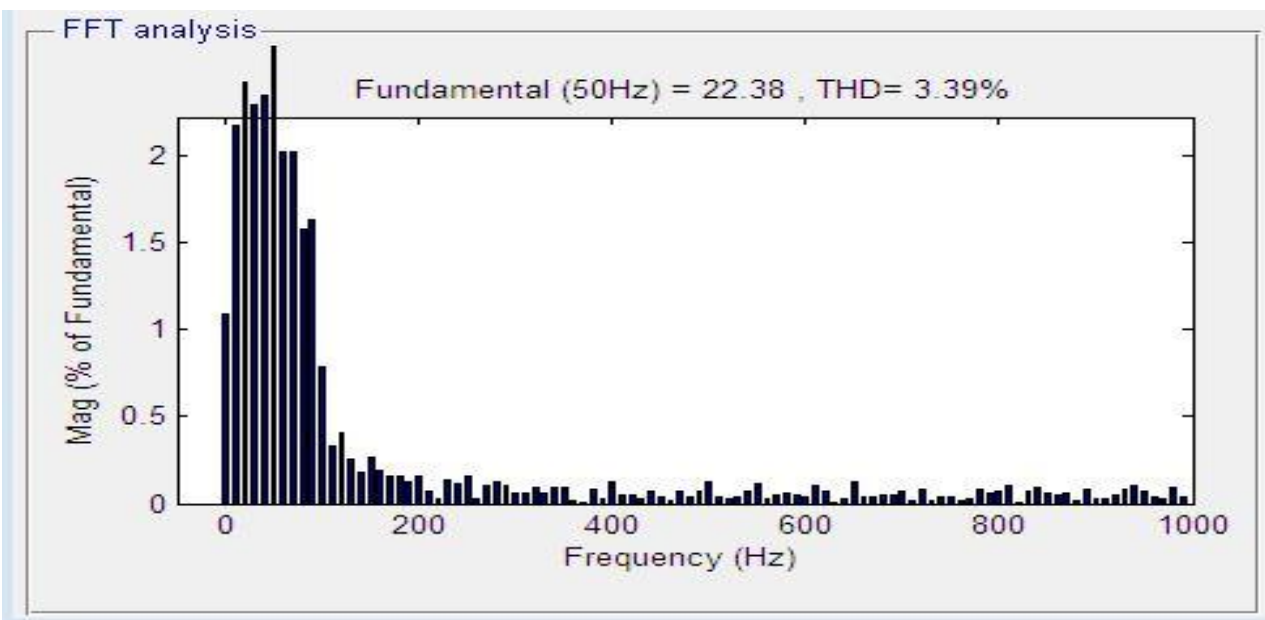


Fig.4.21 THD of source current of UPQC

In Fig.4.21 the THD of source current of UPQC is given. As after application of UPQC THD reduces to 3.39%. The UPQC is successful in reducing THD of source current.

4.4.2 Current Harmonics compensation and voltage swell mitigation

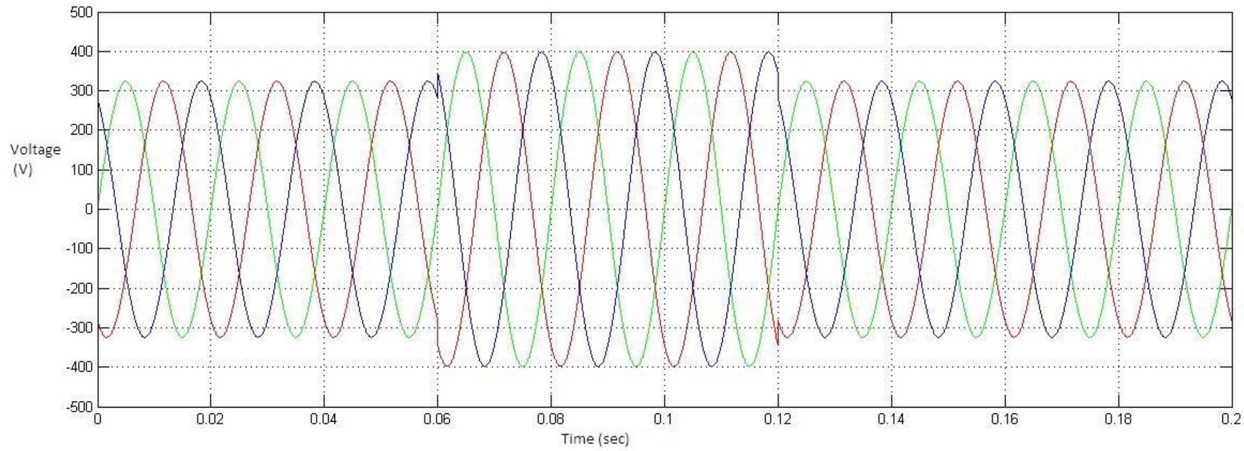


Fig. 4.22 Source voltage of UPQC during swell

In Fig.4.22 source voltage during swell is shown. From time interval 0.06 sec to 0.12 sec there is votage swell , the voltage is around 400 V. This is caused due to capacitor switching or imbalance in source voltage.

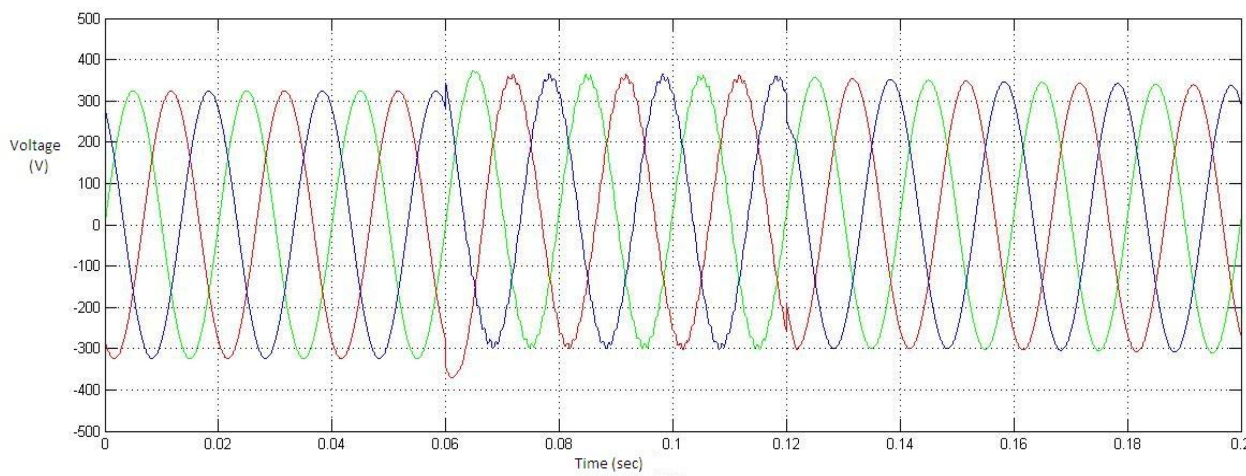


Fig. 4.23 Load voltage of UPQC during swell

In Fig.4.23 the load voltage of UPQC during swell is given it is completely sinusoidal and balanced due to application of UPQC. The series APF part of UPQC is responsible for voltage mitigation. The magnitude of load voltage is now 326 V.

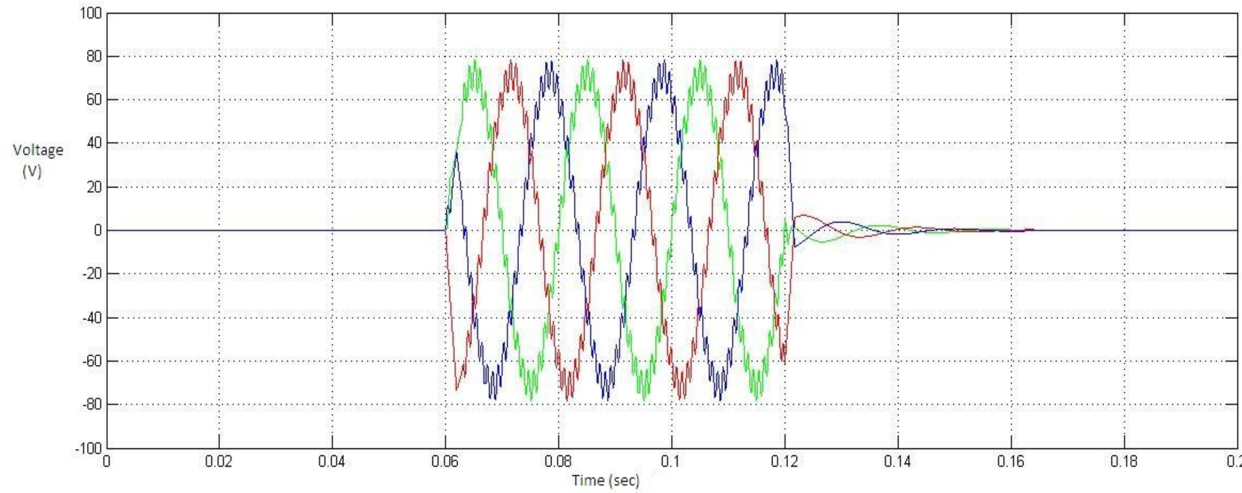


Fig. 4.24 Injected voltage of UQPC during swell

In Fig.4.24 the injected voltage during swell condition is shown. The voltage is injected between time interval 0.06 sec to 0.12 sec. After injecting this voltage the load voltage becomes completely balanced.

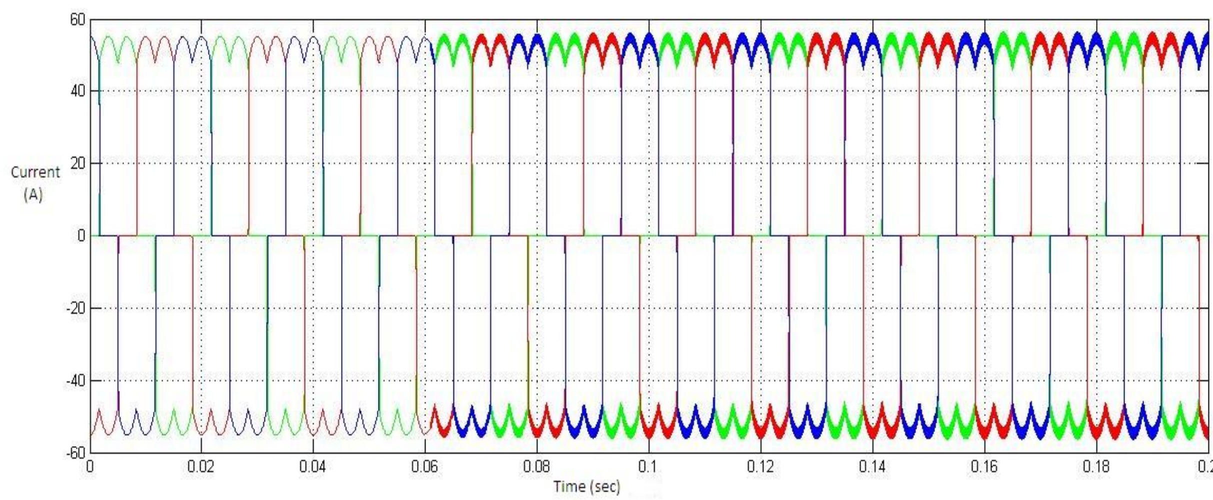


Fig. 4.25 Load current during swell of UPQC

In Fig.4.25 the load current of UPQC during swell condition is shown. It is non- linear due to presence of non-linear loads.

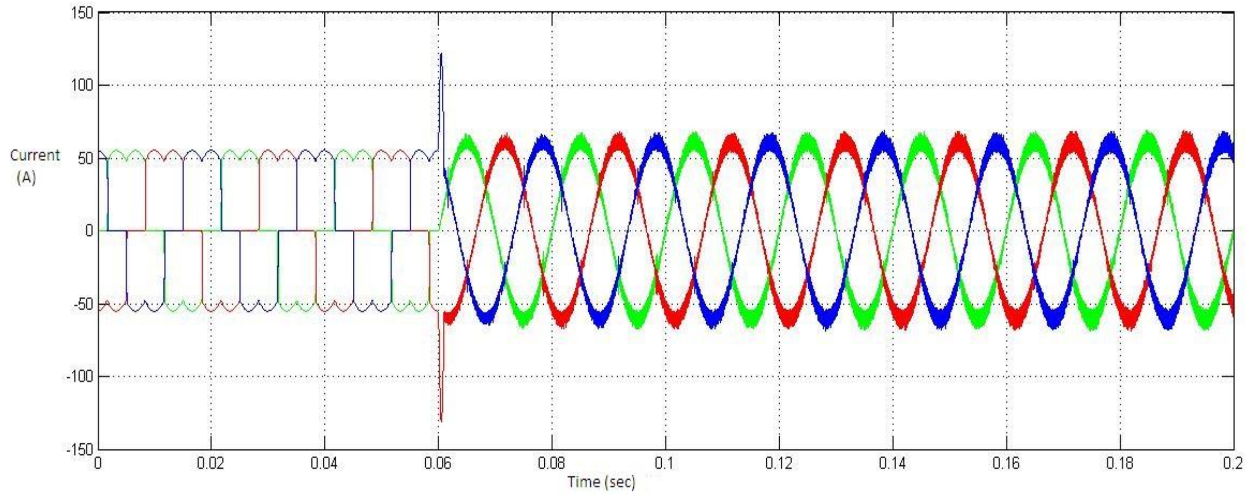


Fig. 4.26 Source current of UPQC during swell

In Fig.4.26 the source current of UPQC during swell condition is shown. The source current is sinusoidal after 0.06 sec as after that the UPQC operates. The source current is sinusoidal mainly due to operation of shunt APF part of UPQC. The operating time of Shunt APF part is controlled by circuit breaker.

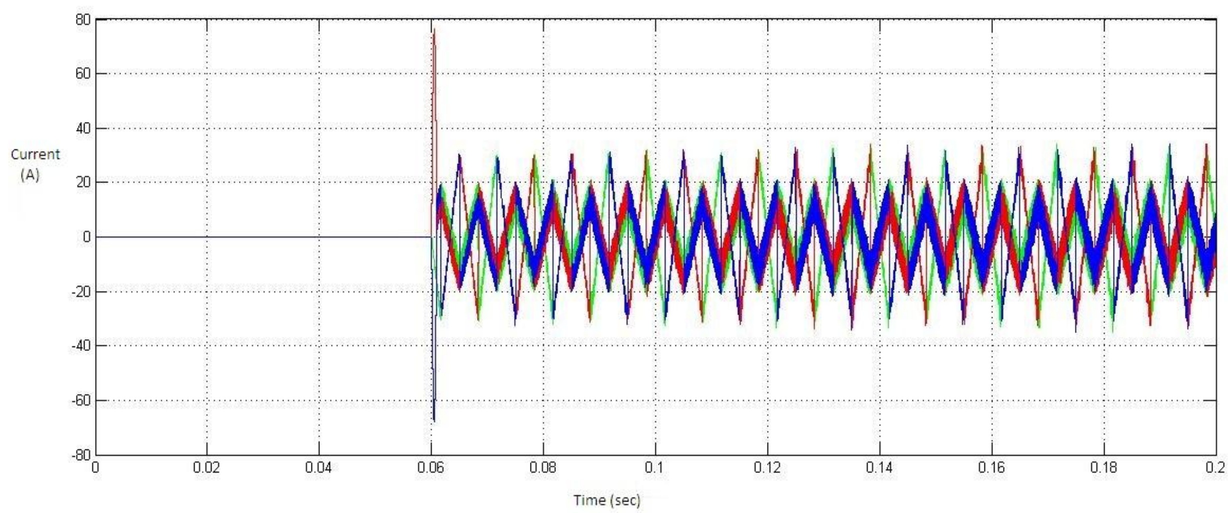


Fig. 4.27 Injected current of UPQC during swell

The Fig.4.27 shows injected current of UPQC during swell condition. Current is injected from time 0.06 sec to compenate for load current non-linearity and make source current completely sinusoidal.

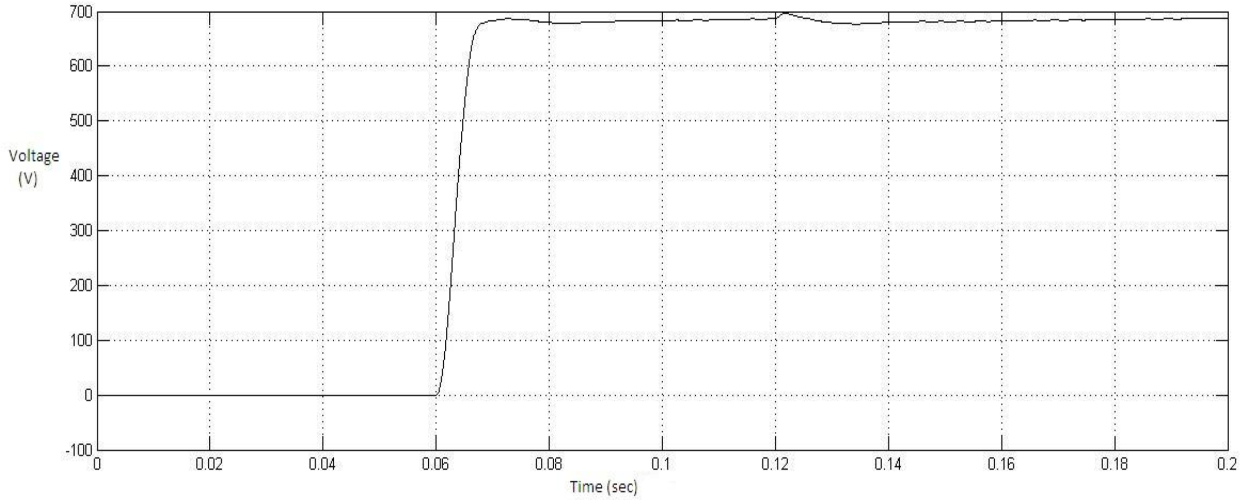


Fig. 4.28 Capacitor voltage during swell

In Fig.4.28 the capacitor voltage during swell is shown.The capacitor voltage rises at 0.06 sec and becomes constant at 700 V. As it always tries to follow the refernce DC voltage.

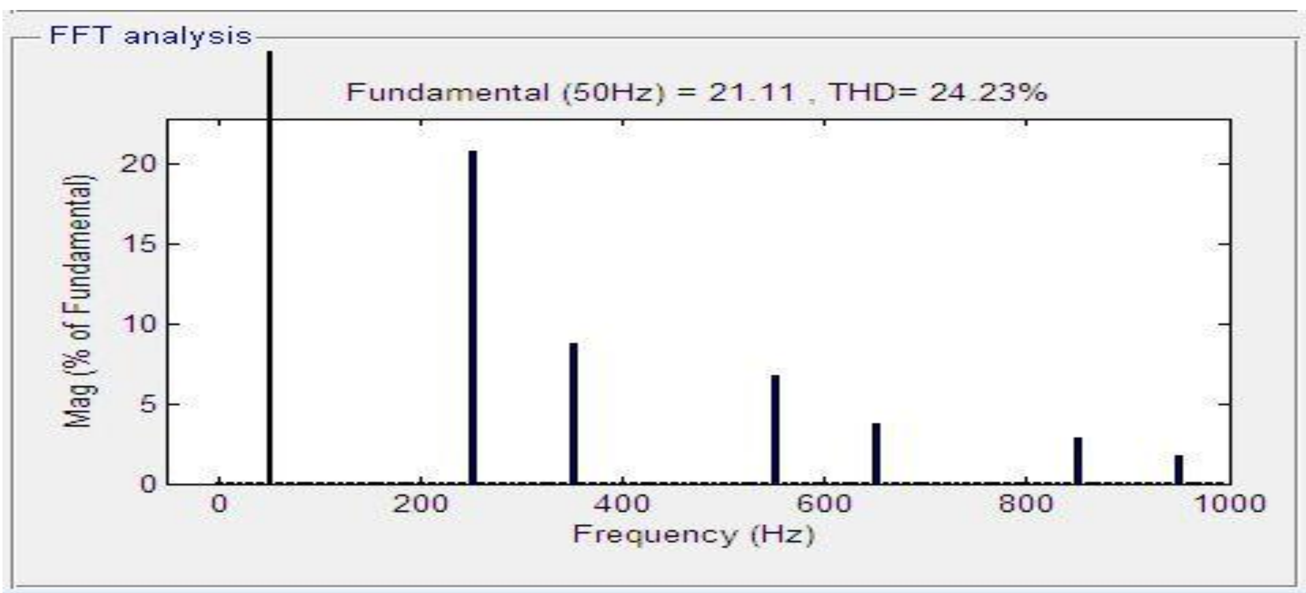


Fig. 4.29 THD of load current

Fig.4.29 shows the THD of load current of UPQC during swell. The load current THD is 24.23% due to presence of non-linear loads. Because of that harmonics contents in load current increases.

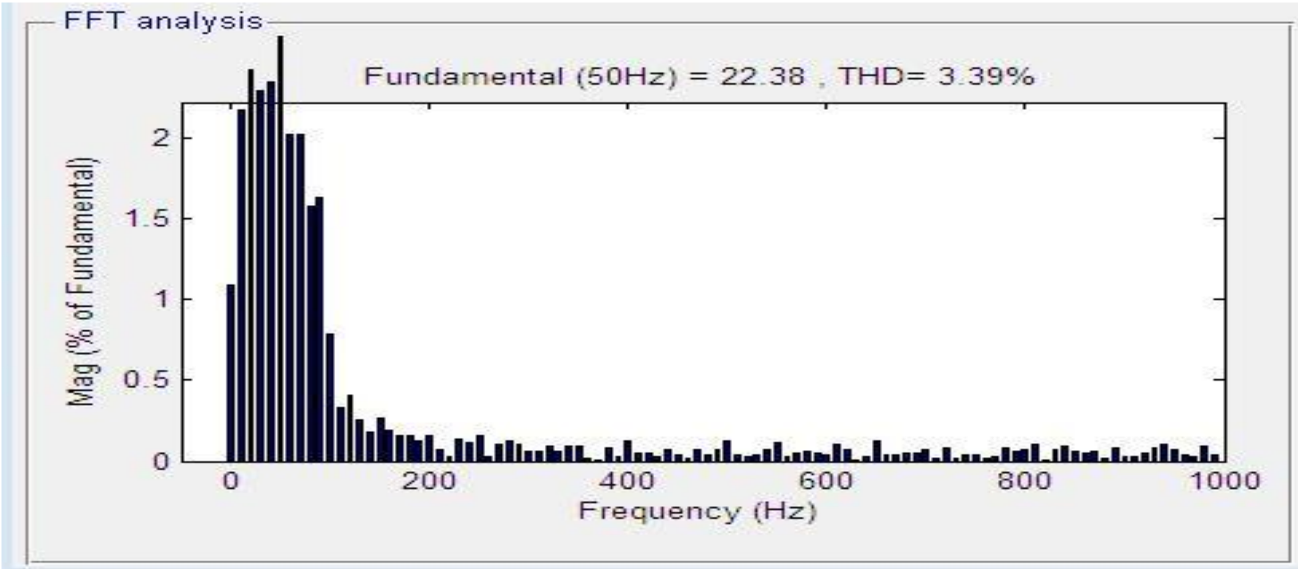


Fig.4.30 THD of source current

Fig.4.30 shows the THD of source current during swell. After use of UPQC the THD of source current reduces 3.39%. As UPQC eliminates all kind of problems due to current harmonics.

Chapter 5

CONCLUSIONS AND FUTURE SCOPE

5.1 Conclusions

5.2 Future Scope

5.1 Concluisons

Unified quality conditioner was studied and investigated in this thesis for power quality enrichement. UPQC is a type of advance hybrid filter which uses series APF for removal of voltage realted problmes like voltage dip/rise, fluctutaion, imbalance and shunt APF for removal of harmonics in current harmonics.What type of problems are there in power quality was studied and discussed. UPQC system is developed and discussed in detail.

The simulink models of Shunt APF , Series APF, UPQC are developed.

- Shunt APF model is developed using "p-q Theory" and control techniques used here is hystersis current controller. The simulation is done and current harmonics are eliminated and current drawn from source is completely sinusoidal. The THD of source current is within the limit that is 5%.
- Series APF model is developed using Park's transformation and controlling techniques used are hystersis voltage controller. The simulation is done and source voltage dip/rise are mitigated and load voltage is made comletely balanced.
- UPQC model was developed by joining Shunt APF and series APF back to back using DC capacitor. The controlling techniques used here are hystersis band controller. The simuation is done and current harmonics are removed and source current is complerely sinusoidal. And the voltage dip/rise in supply side is mitigated and load voltage is perfectly balanced. The THD of source current is within the limit that is lees than 5%.

5.2 Future Scope

The UPQC model can be enhanced and enriched to terminate the power quality problems in a power system. The various ways for doing that:-

- The prototype of this UPQC model can be esatablished in laboratory.
- UPQC model can be established for three phase four wire system for the non-linear load and unstable voltage.
- Here the UPQC model developed was right shunt UPQC, further we can develop model for left shunt UPQC.
- We can connect wind turbines, solar energy system that is renewable source of energy to UPQC to get improved power in consumer ends during serious conditions.

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